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The Trojan

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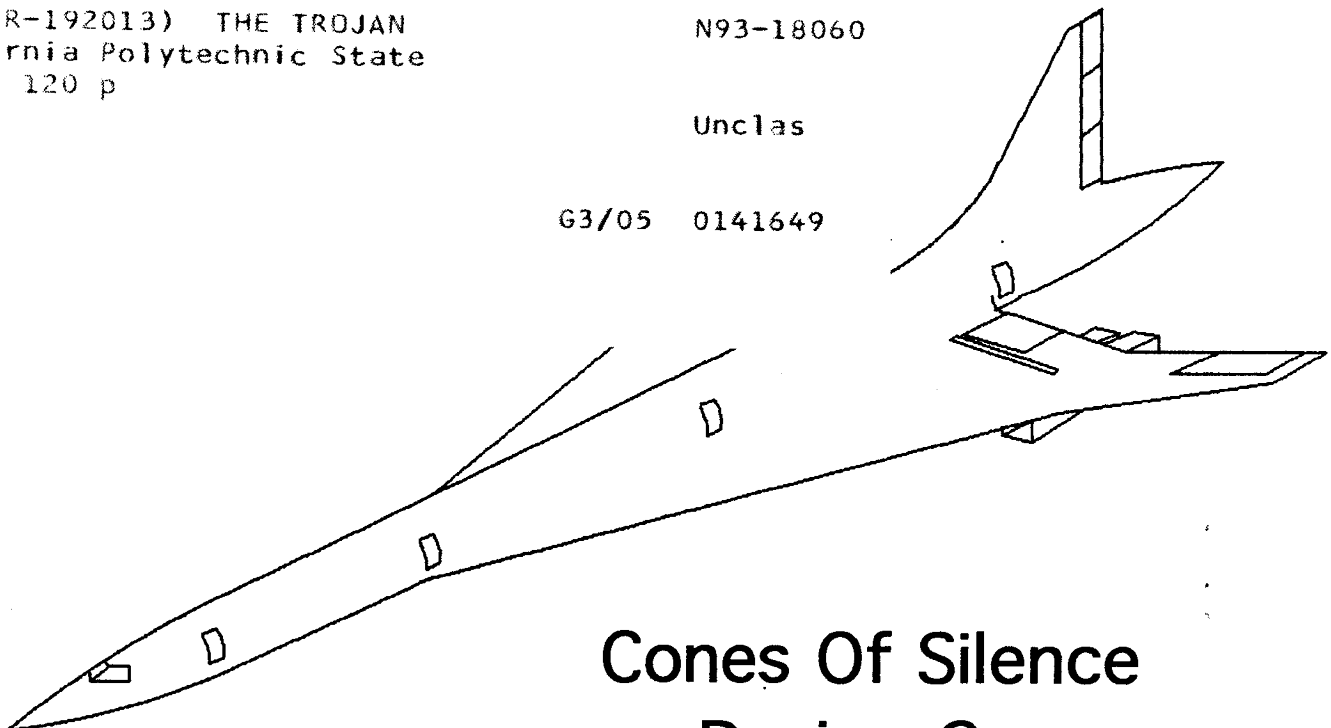

Cones Of Silence Design Group

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ABSTRACT

The Trojan is the culmination of thousands of engineering man-hours by the Cones of Silence Design Team. The goal was to design an economically and technologically viable supersonic transport. The Trojan is the embodiment of the latest engineering tools and technology necessary for such an advanced aircraft. The efficient design of the Trojan allows for supersonic cruise of Mach 2.0 for 5,200 nautical miles, carrying 250 passengers. The per aircraft price is placed at $200 million, making the Trojan a very realistic solution for tomorrows transportation needs. The following is a detailed study of the driving factors that determined the Trojan's superior design

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NOTATION

GENERALIZED SYMBOLS

SYMBOL	DEFINITION	DIMENSIONS
a.c.	aerodynamic center	% of chord
alt	alternate airport	---------
AR	aspect ratio	---------
b	wing span	ft
BAG	baggage	---------
c bar	mean geometric chord	ft
c_l	airfoil lift coefficient	---------
c_m	airfoil pitching moment	
c_t	tip chord	ft
c_r	root chord	ft
C_D	airplanedrag coefficient	---------
CG	center of gravity	---------
CG_x	center of gravity in x-dir.	ft
CG_z	center of gravity in z-dir.	ft
C_j	specific fuel consumption	lb/lb/hr
C_L	airplane lift coefficient	---------
DOC	direct operating cost	USD/nmi
e	Oswald's span efficiency	---------
E	endurence	hr

f	equivalent parisite area	---------
FAR 25	Federal Aviation Report Part 25	---------
I	mass moment of inertia	slug-ft2
Ixx	mass moment of inertia about x-axis	slug-ft2
Ixy	mass moment of inertia about x & y direction	slug-ft2
Ixz	mass moment of inertia about x & z direction	slug-ft2
Iyy	mass moment of inertia about y-axis	slug-ft2
Iyz	mass moment of inertia about y & z direction	slug-ft2
Izz	mass moment of inertia about z-axis	slug-ft2
IOC	indirect operating cost	USD/nmi
kVA	kilovolt ampere	volt ampere
ltr	loiter	---------
L	lift	lbs
LCC	life cycle cost	USD
L/D	lift to drag ratio	---------
M	free stream Mach number	---------
n	airplane load factor	---------
OEI	one engine inoperative	---------
p	perturbed roll rate	rad/sec
pass	pasengers	---------

q	perturbed pitch rate	rad/sec
q bar	free stream dynamic pressure	lbs/ft^2
r	perturbed yaw rate	rad/sec
R	range	nmi
S	wing planform area	ft^2
S_v	vertical tail area	ft^2
t/c	thickness ratio	---------
T_{av}	thrust available	lbs
TFO	Trapped fuel and oil	---------
U	airspeed	ft/sec
u	longitudinal velocity	ft/sec
USD	United States dollars	$
We	empty weight	lb
Wnf	weight no fuel	lb
Wpl	weight of payload	lb
Wto	weight take-off	lb
Wt	weight	lb

<u>GREEK SYMBOLS</u>

α	angle of attack	deg-rad
θ	pitch attitude	deg-rad
ϕ	roll attitude	deg-rad
β	sideslip	deg-rad

SUBSCRIPTS

cr	critical
xx	about x-axis
yy	about y-axis
zz	about z-axis

STABILITY AND CONTROL DERIVATIVES

SYMBOL	DEFINITION	DIMENSION
C_{Du}	$\partial C_D/\partial(u/U1)$	--------
C_{Lu}	$\partial C_L/\partial(u/U1)$	--------
C_{Mu}	$\partial C_M/\partial(u/U1)$	--------
$C_{D\alpha}$	$\partial C_D/\partial\alpha$	rad-1
$C_{L\alpha}$	$\partial C_L/\partial\alpha$	rad-1
$C_{M\alpha}$	$\partial C_M/\partial\alpha$	rad-1
$C_{D\alpha}$	$\partial C_D/\partial(\alpha c/2U1)$	rad-1
$C_{L\acute{\alpha}}$	$\partial C_L/\partial(\alpha c/2U1)$	rad-1
$C_{M\alpha}$	$\partial C_M/\partial(\alpha c/2U1)$	rad-1
C_{Lq}	$\partial C_L/\partial(qc/2U1)$	rad-1
C_{Dq}	$\partial C_D/\partial(qc/2U1)$	rad-1
C_{Mq}	$\partial C_M/\partial(qc/2U1)$	rad-1
$C1\beta$	$\partial C_1/\partial\beta$	rad-1
$Cn\beta$	$\partial C_n/\partial\beta$	rad-1
$Cy\beta$	$\partial C_y/\partial\beta$	rad-1
$C1\beta$	$\partial C_1/\partial(\beta c/2U1)$	rad-1
$Cn\beta$	$\partial C_n/\partial(\beta c/2U1)$	rad-1

$C_{y\beta}$	$\partial C_y/\partial(\beta c/2U1)$	rad-1
C_{1p}	$\partial C_1/\partial(pc/2U1)$	rad-1
C_{np}	$\partial C_n/\partial(pc/2U1)$	rad-1
C_{yp}	$\partial C_y/\partial(pc/2U1)$	rad-1
C_{1r}	$\partial C_1/\partial(rc/2U1)$	rad-1
C_{nr}	$\partial C_n/\partial(rc/2U1)$	rad-1
C_{yr}	$\partial C_y/\partial(rc/2U1)$	rad-1

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1.0 INTRODUCTION

Recent and projected trends in world travel indicate that travel to the Pacific Rim nations will increase at a rate of more than three times that of travel on the North Atlantic routes (Ref. 1). Subsonic aircraft currently flying the Pacific routes have lengthy travel times of up to 14 hours. The demands for more productive forms of air transportation will increase as travel and trade across these Pacific routes increase. The significant reduction in flight time will reduce fatigue of passengers and crew, and improve productivity at their destination.

Advances in the area of supersonic transports have been slow for several reasons. Environmental concerns in the early 1970s kept SST programs from getting off the ground (Ref. 1). Concerns of ozone depletion and noise abatement were arguments of SST opponents. Limited technology placed limits on size, weight, and range and was enough to cause many programs to be dismissed (Ref 1). Fortunately, technology has advanced significantly in the past twenty years. Advances in propulsions have decreased NO_x emissions and noise levels to within acceptable limits. Structural advances have also produced many new and light-weight and durable materials.

The Concorde is the only supersonic transport currently in service. However, its limited market capture severely limits its profitability. A greater range could significantly increase its market capture. The Concorde's shortcomings can be attributed to the limited technology of the era in which it was designed (Ref 5).

The technology of today's aeronautical field is better, and allows for a truly efficient and profitable SST. Our research indicates that the optimal design for an SST is a Mach 2.0, 250 passenger, 5200 nautical mile aircraft. The Trojan meets these needs. It is the embodiment of the "cutting edge".

The following report details the aerodynamics, configuration, propulsion, structure, and performance that make The Trojan the first economically viable supersonic transport.

2.0 MISSION SPECIFICATIONS

2.1 MISSION DESTINATIONS

The Trojan is designed to travel the Pacific Ocean routes with international reserve requirements, resulting in a 5200 nautical mile range. Table 2.1 presents the primary non-stop routes following the mission profile seen in Figure 2.1.

Table 2.1: Non-stop City Pairs

Origin	Destination	Range (n.m.)
Los Angeles	Tokyo	4,700
San Francisco	Tokyo	4,500
Seattle	Tokyo	4,350

Further destinations could be reached over the Pacific with a refueling stopover in Honolulu, Hawaii. Table 2.2 shows the extended city pairs that would have the mission profile of Figure 2.1 to the stopover city to refuel. The mission profile would be again followed from the stopover city to the final destination.

Table 2.2: Extended City Pairs

Origin	Stopover	Destination	Total Range (n.m.)
Los Angeles	Honolulu	Beijing	7,250
		Hong Kong	7,393
		Sydney	6,688
San Francisco	Honolulu	Beijing	7,400
		Hong Kong	7,238
		Sydney	6,688

2.2 MISSION PROFILE

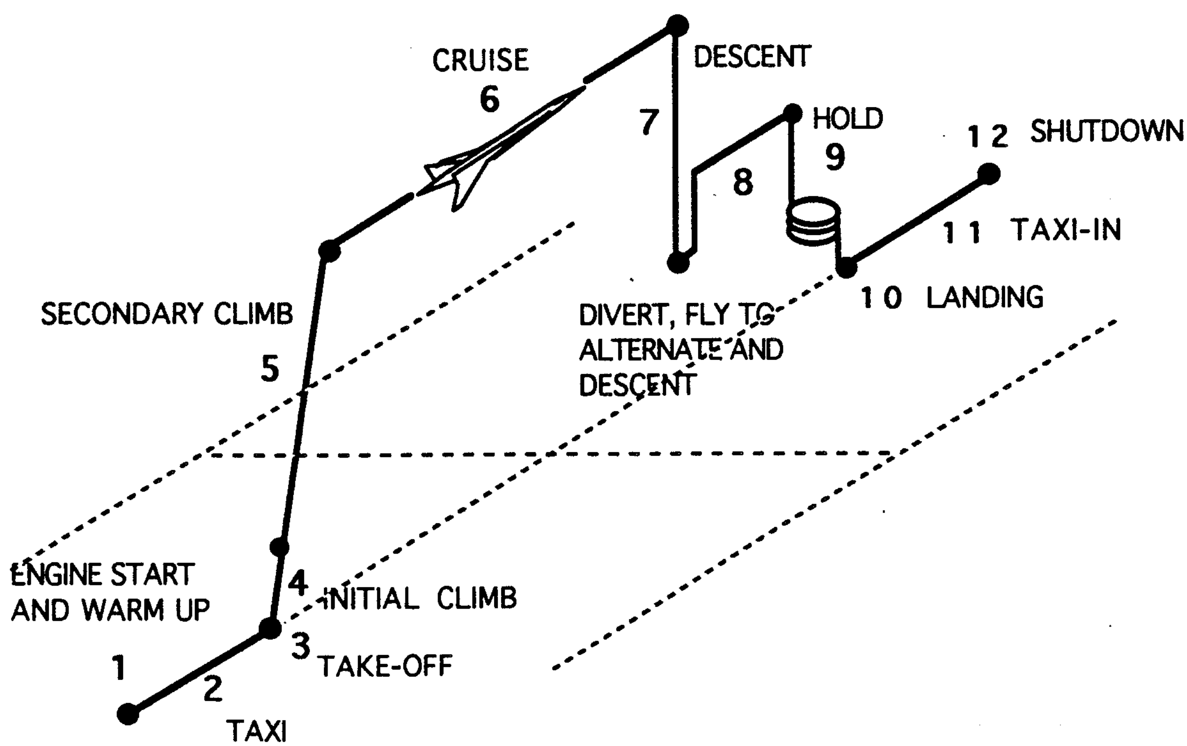


Figure 2.1: Mission Profile

Mission Profile Description

1. Engine start and warm-up (3 minutes)

2. Taxi out (8 minutes)

3. Take-off (185 knots)

4. Initial climb to 1500 ft., through Mach 1.0 (2 minutes)

5. Secondary climb to cruise altitude of 60,000 ft. (18 minutes)

6. Cruise at 60,000 ft. at Mach 2.0

7. Descent to 1500 ft. (24 minutes)

8. Divert, flight to alternate location (200 n.m.), descend to 1500 ft.

9. Hold at 1500 ft. for an hour

10. Landing (193 knots)

11. Taxi-in (5 minutes)

12. Shutdown

3.0 SIZING ANALYSIS

3.1 WEIGHT SIZING

Various weights associated with the Trojan were sized in two phases. Phase one sizing was done using the method of Reference 2. The method of fuel fractions was used to determine the fuel weight. This was accomplished by dividing the mission into different phases, such as takeoff, cruise, and hold. The amount of fuel used for each phase was determined from Breguet range and endurance equations (Ref. 2). In some cases the equations could not be used and the fuel fractions were determined from tables and graphs of similar aircraft (Ref. 1). Other parameters used in the initial fuel sizing such as specific fuel consumption, lift to drag ratios, etc were determined using other aircraft with a similar mission (Ref. 1). Using the preliminary fuel weight estimation, the takeoff and empty weights of the Trojan were determined using an iterative process. This iterative process was based on the linear relationship between the logarithms of empty weight and takeoff weight as shown in Reference 2.

Phase two of the weight sizing of the Trojan was done by calculating the individual weights of the major components of the aircraft. The weights of some of the components were known and these exact values were used. The weights of the rest of the components were calculated using the empirical equations of Reference 3.

The final aircraft weights of the Trojan are shown in Table 3.1. The fuel fraction calculated by the above method for the Trojan is 0.52.

Using the equations derived in Reference 2, the sensitivities to change in important parameters were found. These sensitivities are shown in Table 3.2. The Trojan was most sensitive to Cj during cruise.

Table 3.1: Preliminary Weight Sizing Results

Takeoff Weight		650000 lbs
Empty Weight		251000 lbs
Fuel Weight		349000 lbs
Payload Weight		50000 lbs

Table 3.2: Sensitivities

Wto to Wpl (lb/lb)	12.6
Wto to We (lb/lb)	2.23
Wto to R (lbs/mi) cr	550
Wto to E (lbs/hr) ltr	425000
Wto to R (lbs/mi) alt	1860
Wto to V (lbs/mi/hr) cr	-2490
Wto to V (lbs/mi/hr) alt	-936
Wto to Cj cr (lbs/1/hr)	2890000
Wto to Cj ltr (lbs/1/hr)	708000
Wto to Cj alt (lbs/1/hr)	356000
Wto to L/D cr (lbs)	-329000
Wto to L/D ltr (lbs)	-47200
Wto to L/D alt (lbs)	-23800

3.2 PERFORMANCE SIZING

In order to determine the thrust loading and wing loading necessary for the Trojan, various performance requirements were calculated as a function of wing loading and thrust loading. These parameters included FAR 25 landing and takeoff requirements, cruise performance, and maneuvering performance (Reference 2). Figure 3.1 is a plot of these constraints.

It can be seen from Figure 3.1 that the requirements that sized the Trojan are FAR 25.121 (one engine inoperative, gear down , and takeoff flaps) and stall speed at takeoff. It is also seen from Figure 3.1 that the design point is a wing loading of 75 psf and a thrust loading of 0.45.

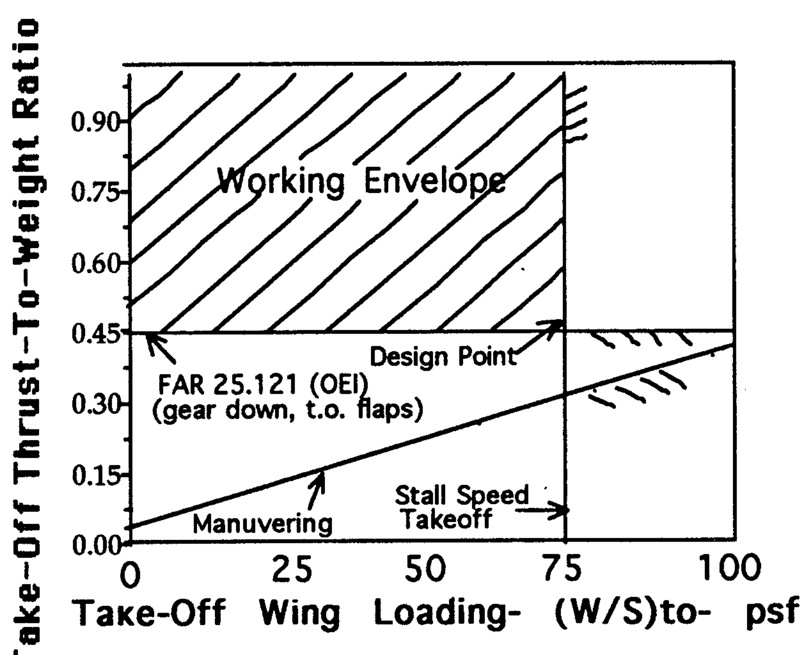


Figure 3.1: Thrust Loading versus Wing Loading for Takeoff

4.0 AIRCRAFT CONFIGURATION

4.1 GENERAL CONFIGURATION

The Trojan is a low, arrow wing, four engine aircraft, as shown in Figure 4.1 on the following page. It has no horizontal tail and incorporates aerodynamic tailoring for favorable performance characteristics during supersonic flight.

Because of the supersonic requirement of the aircraft, there was a need to perform maximum aerodynamic tailoring. Aerodynamic tailoring can lead to significant improvements in performance characteristics, such as L/D ratios.

The Trojan's design incorporated blending of the wing to the fuselage, as shown in Figure 4.2. The most viable way to blend the wings was to completely eliminate all of the passenger windows. Eliminating passenger windows also results in considerable structural weight savings.

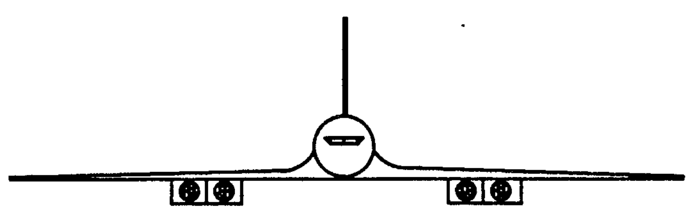
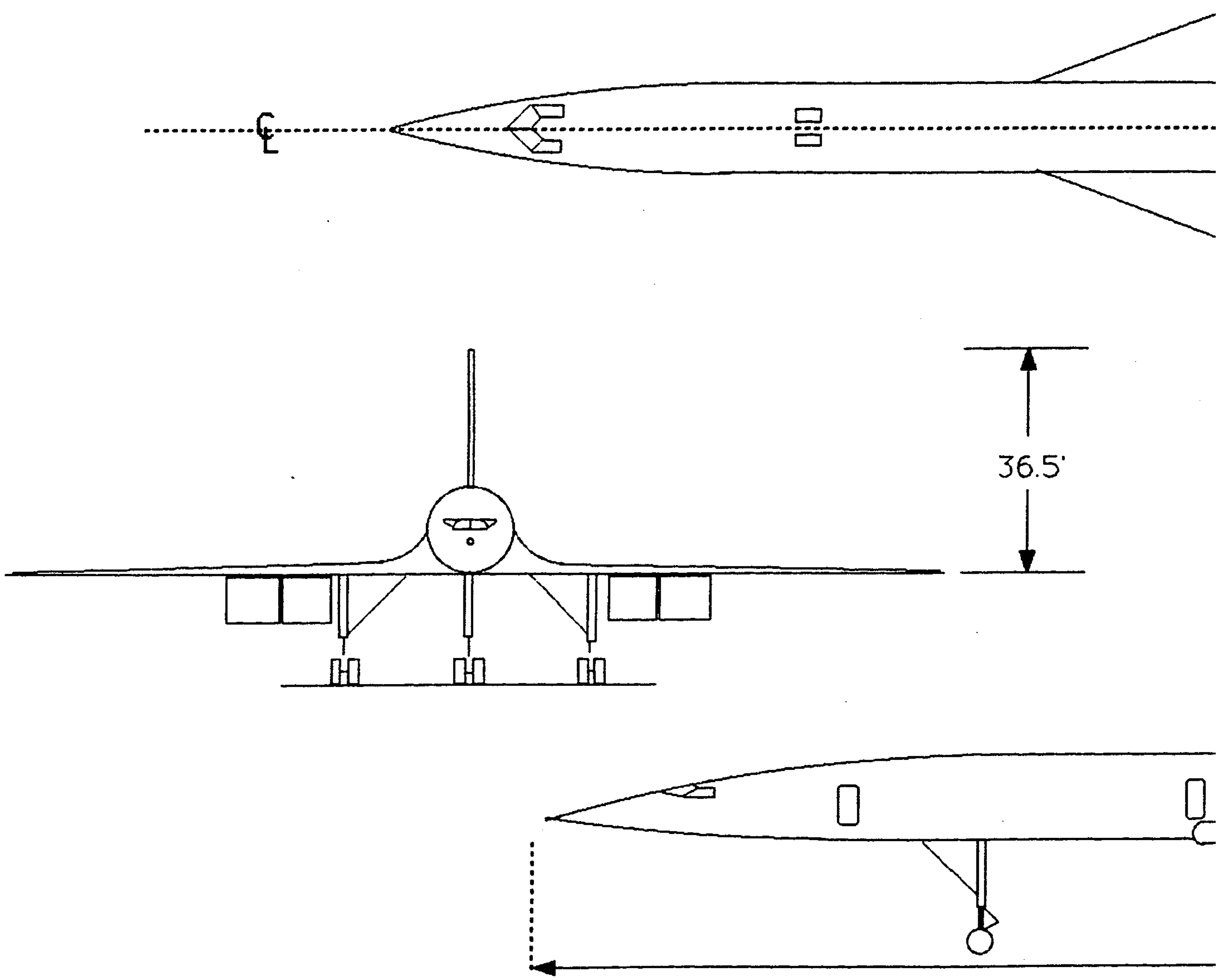


Figure 4.2: Trojan Front View

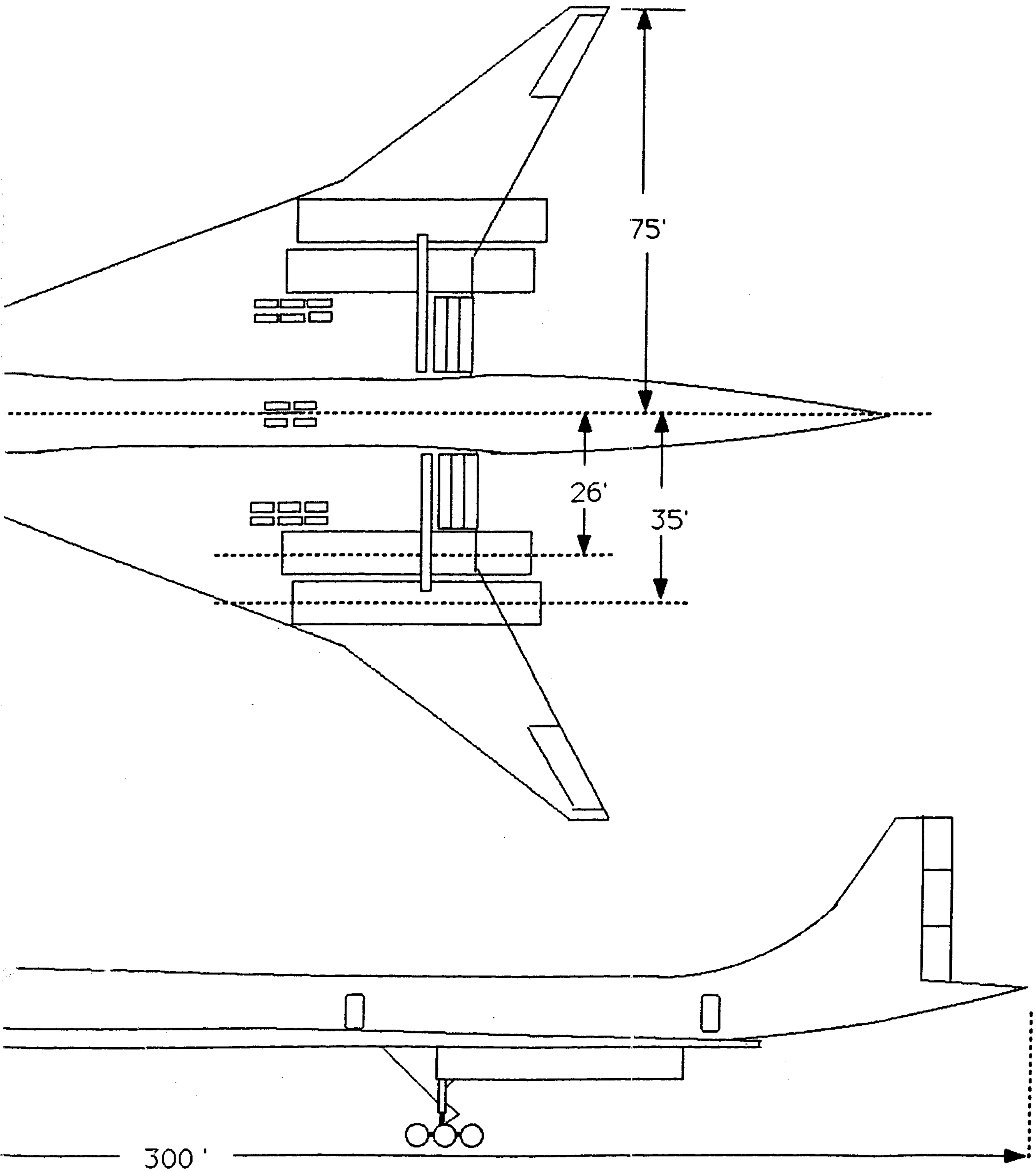
There are extremely high pressure differences between the inside and outside of the fuselage during supersonic flight. To design windows capable of supporting those loads would require significant structural reinforcement. That would not only lead to increased weight, but also increased production costs.

FOLDOUT FRAME 1.

Figure 4.1: Aircraft Configuration



FOLDOUT FRAME 2



4.1.1 WING PLANFORM

The arrow-wing configuration was chosen to be the best suited to The Trojan's mission. The decision was made after reviewing trade-off studies between delta-wing, variable sweep, and oblique wing planforms. Examples of each are shown in Figure 4.3.

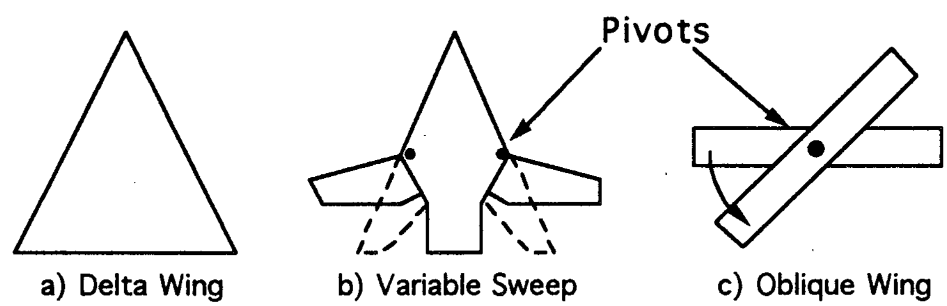


Figure 4.3: Comparison of Wing Planforms

Delta and cranked delta wings, because they are highly swept, are ideal for high speed flight. They have low compressibility drag characteristics and offer good performance at higher angles of attack. Because of their design, they require less reinforced structures than arrow-wings, which results in an overall weight savings for the delta-wing. But their low speed performance is considerably worse than an arrow-wing.

Variable sweep wings offer the best combination of low and high speed performance. The low sweep angles are good for take-off and landing performance, as well as good handling characteristics. Variable sweep offers the optimum values of L/D throughout a wide performance envelope. (Ref. 3) However, variable sweep offers improved performance at a price. The pivot and system required to change the wing angle add a considerable amount of weight. Another problem is the location of the pivot and system.]

Oblique-wing designs offer many of the same advantages as the conventional, variable sweep wings. But, they only require one pivot, thereby reducing the weight penalty of the dual pivot system. The divergence angle of the forward panel will require some increase in weight and partially offsetting the pivot weight advantage. (Ref. 3)

The weight penalty incurred by the massive pivots required by the swing and oblique wings far outweighed their performance capabilities. Although the arrow-wing too has a structural weight penalty, the higher lift over drag (L/D) ratios and lower direct operating costs were significant enough to warrant incorporating it into the Trojan. (Ref. 23) The flutter problem associated with the aft section of the arrow wing also needs to be overcome.

4.1.2 LOW WING

The main reason for incorporating a low wing design was the need for stowage space for the main landing gear. As shown in Figure 4.4, the main gear require a significant amount of volume to stow.

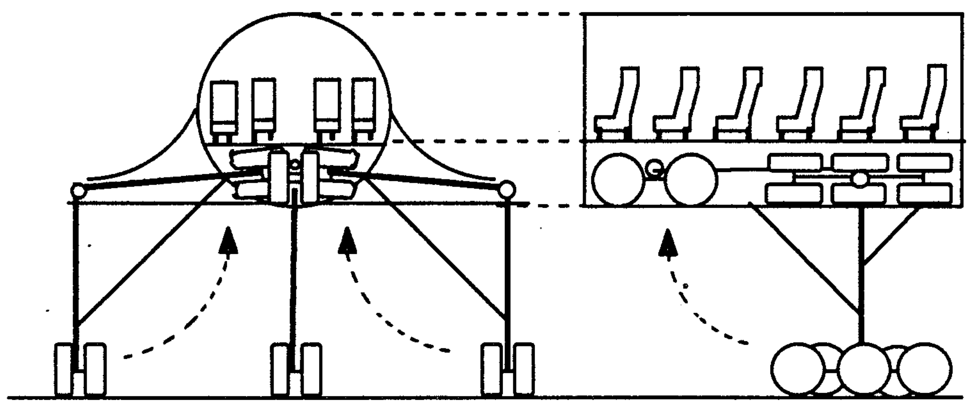


Figure 4.4: Main Gear Retraction for the Trojan

Without a low-wing configuration, there would be a need for fairings to enable the gear to fully retract into the fuselage. As a result, there would be a significant drag penalty at supersonic flight. Furthermore, it would make aerodynamic tailoring much more difficult to accomplish.

4.1.3 EMPENNAGE SELECTION

A vertical tail, canards, and a horizontal tail were the choices for the Trojan's design. Originally, the design incorporated a small retractable canard, as shown in Figure 4.5.

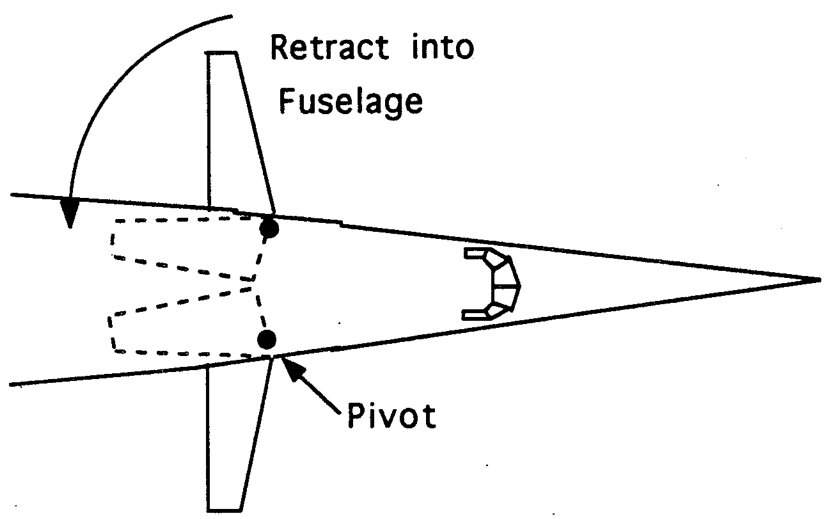


Figure 4.5: Canard Retraction for the Trojan

The purpose of the canard was to aid in take-off, landing, and the subsonic flight performance. At take-off and landing, the arrow and delta wing planforms have relatively poor performance. But, after all of the calculations were performed, the canard did very little to increase the landing and take-off performance. Furthermore, the weight penalty of the pivot required for the retraction far exceeded any improvements in performance.

The compartment in which the canard was to retract into also posed structural problems. It would have required highly reinforced structures in the front of the aircraft. The space required to retract into would have meant enlarging the fuselage diameter in that area.

Federal regulations require that redundancies be designed into the retraction system. That meant that the elevons needed to be sized so that in case of a canard malfunction, the aircraft could still take-off and land. By sizing elevons for a canard malfunction, then the need for the canards was effectively eliminated.

After the canards were eliminated form the Trojan's design, the next step was to examine the need for a horizontal tail. Originally, with the canards, there was no need for a horizontal. But, since the canards had been eliminated, the aircraft needed a surface for longitudinal control power. Again, since the elevons had been sized to provide the necessary control power, the addition of a horizontal tail was also deemed unnecessary. Although, adding a horizontal would have enabled the use of a smaller elevon. But, the addition of a tail would also have meant a c.g. shift to the rear, making the Trojan more unstable. The greater instability would have required a larger horizontal. It would have added a significant increase in the structural weight. A tradeoff was made: reduced structural weight for larger elevons.

5.0 WING DESIGN

5.1 PLANFORM DESIGN

The arrow wing configuration was the best suited for the mission of the Trojan. This decision represents a trade study of other possible configurations: straight, delta, swing and oblique wings (Table 5.2). High wave drag at supersonic speeds for the straight wing dissmissed this configuration. The structural design and weight problems of the swing wing and oblique wing outweighed their performance capabilities. A study of SST planforms by McDonnell Douglas (Ref. 4) showed higher lift to drag (L/D) ratios and lower Direct Operating Costs (DOCs) for the arrow wing over the delta wing configurations. Figure 5.1 and Table 5.1 presents the Tojan's planform geometry.

Table 5.1: Tojan Wing Geometry

S (ft^2)	8652
b (ft)	154
A R	2.74
λ	.06
c_r (ft)	123
c_t (ft)	7
c (ft)	61
Λ_{LE} (deg)	69°, 52°
Λ_{TE} (deg)	28°, 0°
t/c	.04
i_w (deg)	1°
ε_t (deg)	0°
Γ_w (deg)	0°

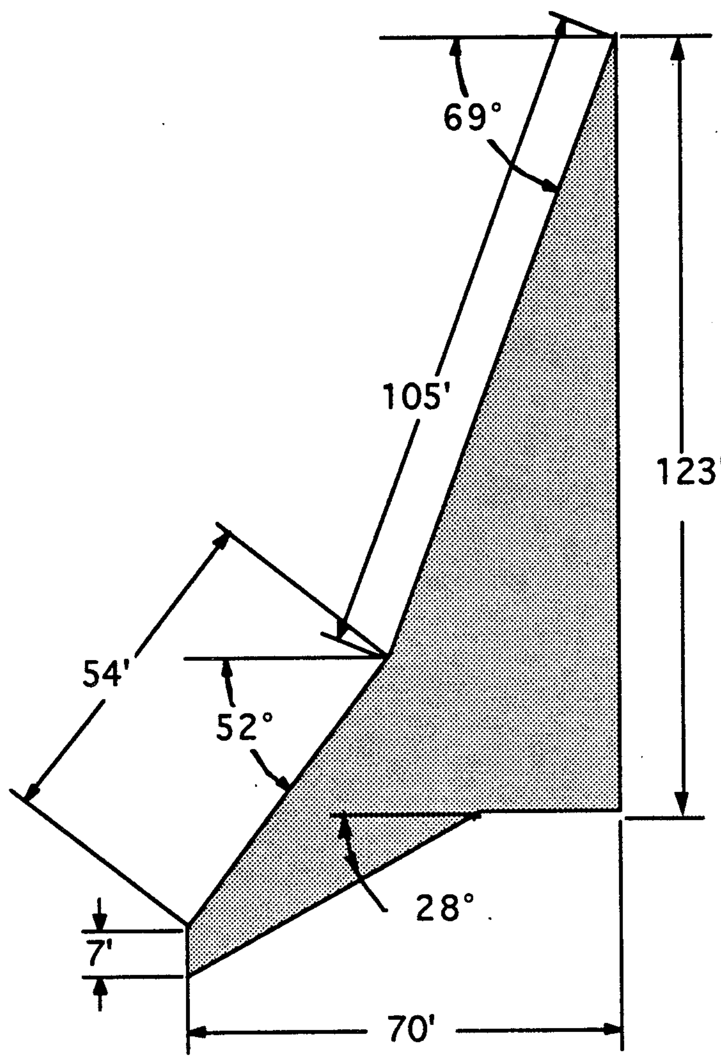
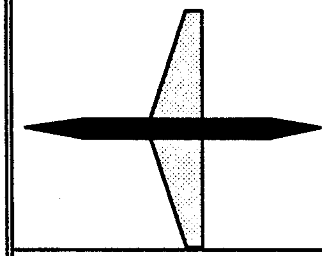
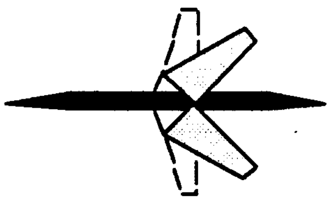
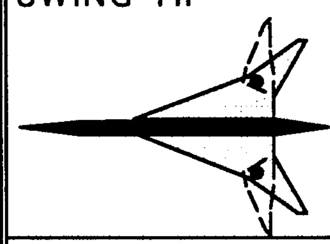
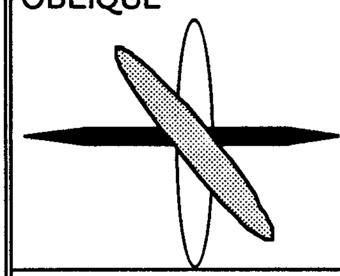
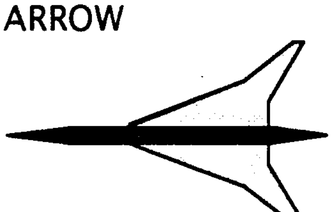


Figure 5.1: Trojan Wing Geometry

Table 5.2: Trade Study of Wing Configuration

CONFIGURATION	ADVANTAGES	DISADVANTAGES
STRAIGHT 	• high wing loading • simple construction • good subsonic performance	• high wave drag at supersonic
SWING 	• good performance sub and supersonic	• high complexity, weight and cost due to sweep mechanism • high maintenence
DELTA (CRANKED) 	• good supersonic performance • high stall angle of attack	• longer take-off run • poor area distribution
SWING-TIP 	• good performance sub and supersonic	• high complexity, weight and cost due to sweep mechanism
OBLIQUE 	• good performance sub and supersonic	• complex stability and control • high weight penalty for pivot • unconventional design
ARROW 	• best L/D • simple construction • high stall angle of attack	• flutter of aft wing section • moderate subsonic performance

Wing Area(S)

The wing area of 8652 ft.^{2} was selected to accommodate the design point wing loading of 75 lb/ft^2 (see Fig. 3.1)

Sweep Angle (Λ)

The leading sweep of a planform has much effect in supersonic flight. To reduce drag it is necessary to sweep the leading edge behind the Mach cone. The Trojan's cruising speed of Mach 2.0 sets the Mach cone angle at 60°. There are two sweep angles associated with the Trojan's arrow wing design; inboard sweep and outboard sweep. The inboard sweep and the planform area behind represents the majority of the wing area. With the parameters of Mach cone angle, aspect ratio and wing area the inboard sweep angle was established at 69°. This permits the Mach number normal to the leading edge to be subsonic even at Mach 2.0 cruise speed. The outboard sweep angle of 52° was designed to extend out of the Mach cone. The problem of drag caused by the sweep into the supersonic region is worth the costs to obtain the desired higher aspect ratio.

Aspect Ratio (AR)

The maximum subsonic L/D increases by approximately the square root of an increase in aspect ratio. On the other hand the wing weight also increases by about the same factor (Ref.5). Induced drag, which varies inversely with a change in AR, called for the

Trojan's to be as large as structurally feasible. The Trojan's AR is maximized at 2.74 keeping in consideration the structural weight penalty.

Thickness Ratio (t/c)

The low thickness ratio for the Trojan is designed at 4% to decrease wave drag at supersonic speeds while taking into consideration structure weight and volume for fuel and control surface actuators.

Taper Ratio (λ)

The taper ratio affects the lift distribution along the wing span. According to the Prandtl wing theory (Ref. 6), induced drag is minimized when the lift distribution along the wing is elliptical. For an aft swept wing there tends to be a component of spanwise flow creating more lift outboard thereby a nonelliptical lift distribution. Increasing the taper ratio would create a more elliptical lift distribution. For supersonic flow, the wave drag created by the increase in taper ratio is far greater than the induced drag produced by a decreased taper. The Trojan's taper ratio is 0.06, which agrees with the trend of pervious aircraft (Ref. 6).

Twist (ε_t)

The are two types of wing twist are aerodynamic and geometric. Aerodynamic twist is the angle between the zero-lift angle of the airfoil at the root to the zero-lift angle of the airfoil at a point along the span. Geometric twist is the change in the airfoil angle of incidence, measured with respect to the incidence at the root airfoil. Both of these twists are used to reshape the lift distribution of a planform. An attempt to use twist to optimize the lift distribution would only be valid at one lift coefficient. At the other lift coefficients the lift distribution would worsen. The Trojan employs no geometric twist. There is a slight aerodynamic twist due to the two types of airfoils being used, subsonic and supersonic. The inboard subsonic airfoil has a slight camber while the outboard supersonic airfoil is symmetrical. The aerodynamic twist effect is considered minimal due to the small camber relative to the chord lengths. Due to the diffuculty in obtaining the effect of twist computerized soultions are employed. This was not possible for this level of preliminary design.

Incidence (i_w)

Wing incidence is designed to minimize drag at some operating condition, usually cruise. For a passenger transport the designer must take into consideration the slope of the cabin floors so the flight attendants are not pushing carts uphill. The incidence angle is usually set using wind tunnel data. Since this was not feasible for this preliminary design of the Trojan, the incidence angle is 1° as suggested by Reference 6 for passenger transports.

Dihedral (Γ_w)

The dihedral effect is most important in the lateral stability and control for an aircraft. Due to the complications in the structural support of a dihedral wing and the superior triple redundant flight control systems, the Trojan employs no built in dihedral.

Wing Vertical Location

The Trojan has a low wing placement. The structural support of the wing and landing gear stowage were the driving factors in this decision. The low wing support box will run through the bottom of the fuselage. The drag interference associated with a low wing design will be compensated with a blending of the wing and the fuselage. The wing box placement does eliminate potential baggage compartment volume, but the required volume specified by the RFP is still met: 6.5 / 6.0 cu. ft. for 1st class and business class respectivley.

5.2 AIRFOIL SELECTION

There are two types of airfoils used on the Trojan, subsonic and supersonic (see Fig.5.2). The majority of the wing (inboard) is swept behind the Mach cone to reduce wave drag at the cruise speed of Mach 2.0. A subsonic airfoil can be used because the component of flow velocity normal to the leading edge of this area of the wing if subsonic. The tips of the wing (outboard) are outside the Mach cone, resulting in a need to employ a supersonic airfoil design. Blending of the two airfoils is necessary where the Mach wave cuts over the wing.

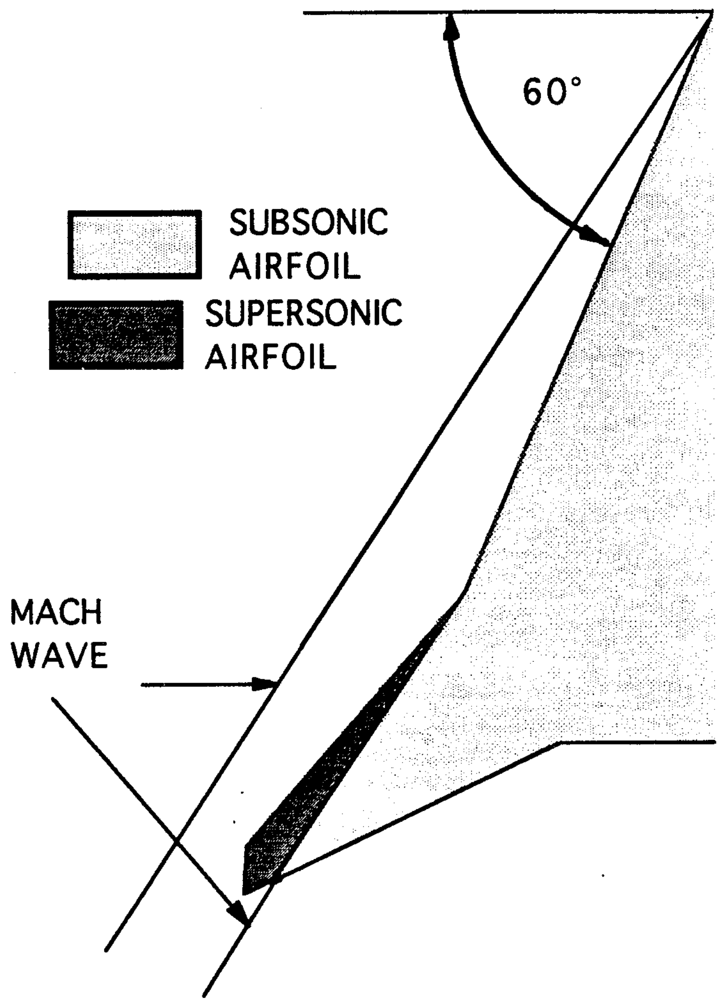


Figure 5.2: Airfoil Locations

<u>Subsonic Airfoil</u>

The inboard planform airfoil is the NACA 64A204 (Fig. 5.3). This decision was based on the need for a slightly cambered, low thickness airfoil. A cambered airfoil has better performance at subsonic speeds and more lift at cruise than a symmetrical airfoil. The 4% thickness will keep drag low but will still allow volume for fuel and actuators. No material was found on any NACA 4% thickness airfoils, therefore a NACA 64A210 (Ref 10) was modified down to a 4% thickness airfoil. This was done by scaling down y-axis % by a factor of 0.4 while leaving the X/C-axis unmodified (calulations in Appendix 5). Table 5.3 shows the airfoil characteristics, obtained by extrapolating existing data from Reference 10 to met the 4% thickness modification, of the modified airfoil.

Table 5.3: NACA 64A204 Characteristics

$Cl_{\alpha=0}$	0.425
$Cl_{l=0}$	-1.3
Cl_{max}	0.7
$C_{mc/4}$	-0.21
t/c_{max}	4%
location of t/c_{max}	40%c
$Cl\alpha$	0.108/deg.
a/c subsonic	0.256
a/c supersonic	0.5

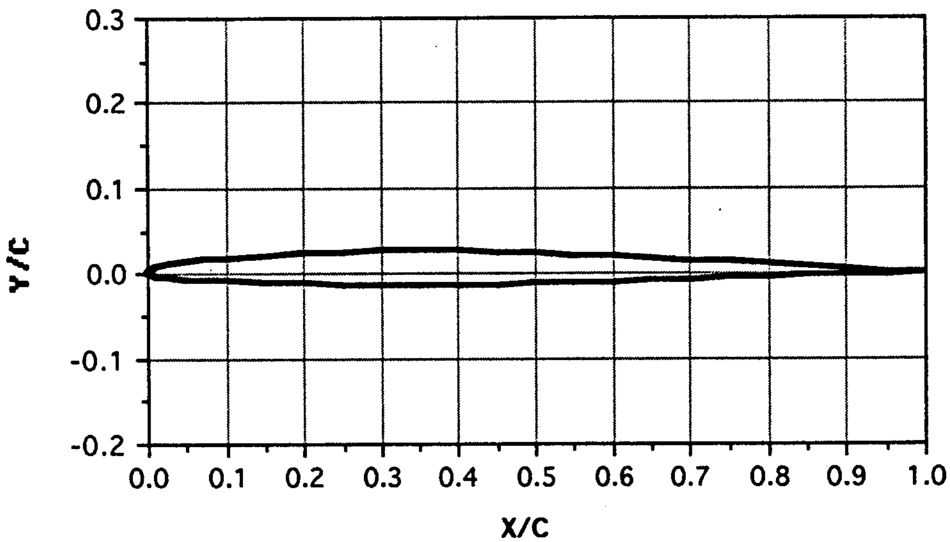


Figure 5.3: NACA 64A204 Airfoil

Supersonic Airfoil

The outboard planform is a symmetrical double wedge (Fig. 5.4). The double wedge is chosen over a biconvex or modified double wedge because the wave drag is less than the other choices (App. 5). This airfoil has a sharp leading edge to minimize the supersonic wave drag. The airfoil will not produce as much lift as a cambered airfoil. The need to keep the drag down overshadows the need for more lift. The inboard portion of the wing will produce the majority of lift.

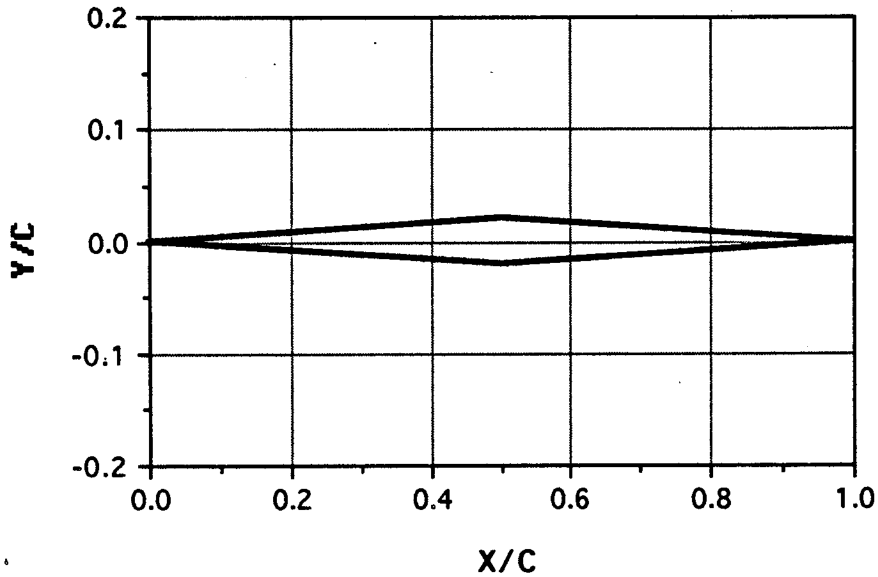


Figure 5.4: Supersonic Airfoil

5.3 CONTROL SURFACES

Elevons

Elevons are the control surfaces that are elevators and ailerons combined. This was necessary due to the Trojan's tailless configuration. The elevons were sized to meet the control power needs (App. 13). These control surfaces were placed as far aft and outboard as possible to created the greatest pitching moment when needed (Fig 5.5).

Spoilers

The spoilers are deployed upon landing. They cause the flow over the wing to detach, creating drag to aid in the braking of the Trojan. The spoilers are placed in front of the flaps (Fig. 5.5) to destroy the extra lift added by the flaps which also helps in the braking of the Trojan.

5.4 HIGH LIFT DEVICES

Triple slotted flaps enables the Trojan to increase lift on take-off and reduce velocity upon landing. Triple slotted flaps, although heavier than other types of flaps, gave the highest increase in Clmax. These flaps increased the CL sufficiently so that leading edge flaps were not necessary. The wing control surfaces were sized using the method of Reference 6 (Appendix 5). The flaps are placed inboard (Fig 5.5) to acquire the amount of flapped area necessary, due to highest chord length, while at the same time minimizing the flap width. The reduction of flap width permits more flexibility for engine placement and control surface location.

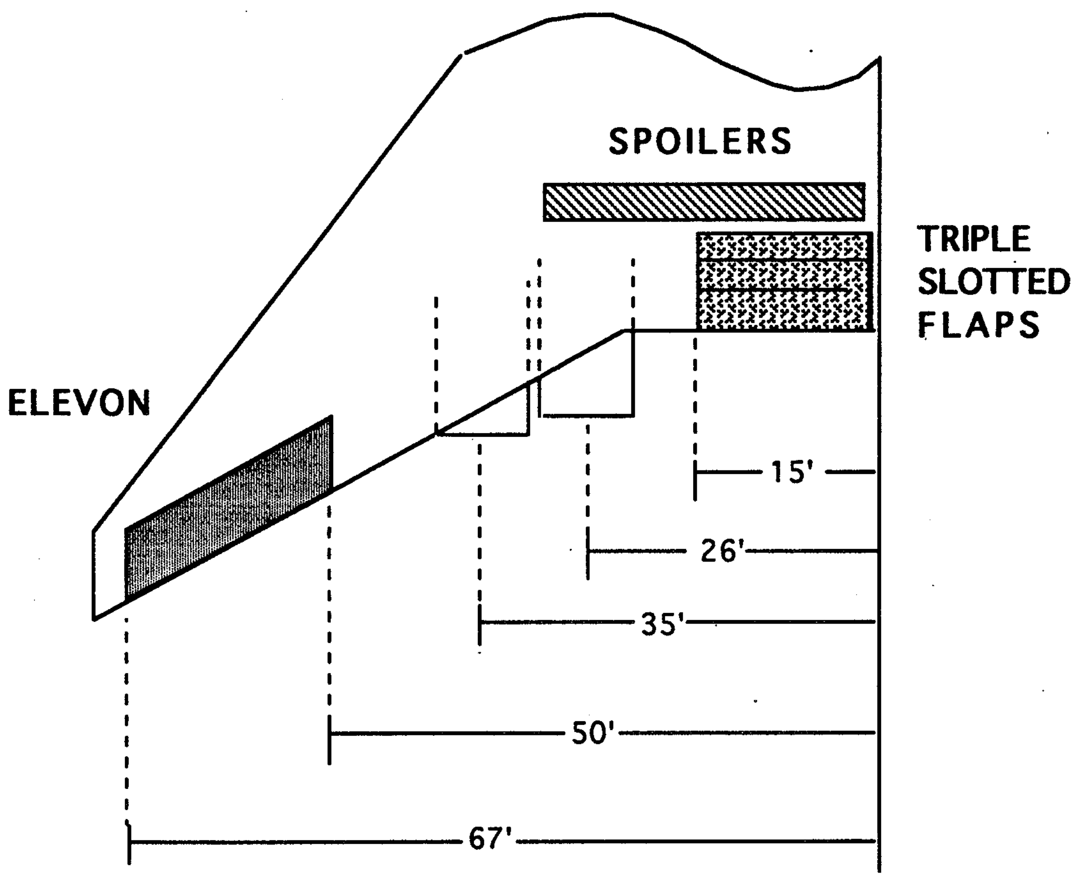


Figure 5.5: Control Surfaces and High Lift Devices

6.0 FUSELAGE DESIGN

6.1 AREA RULING

Area ruling was used to minimize wave drag of the Trojan during the supersonic flight regime. The cross-sectional areas of the aircraft were taken every ten feet, at the 60° Mach angle. These areas were plotted against the longitudinal station and compared with the Sears Haack II line, the ideal shape to minimize wave drag. (Fig.6.1). The major areas of deviation from the ideal Sears Haack plot was located at the forward and center sections of the fuselage. To lower the wave drag on the Trojan, tapering was required on the fuselage forward section and "coke bottling" on the center section. These area ruling modifications permitted the Trojan's wave drag profile to further approach the ideal Sears-Haack curve.

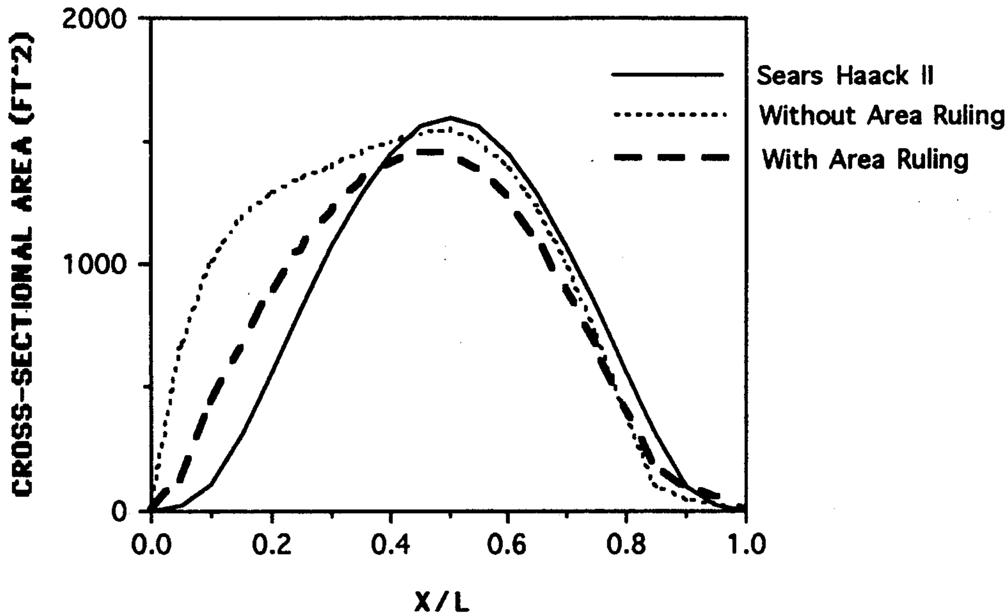


Figure 6.1: Area Ruling

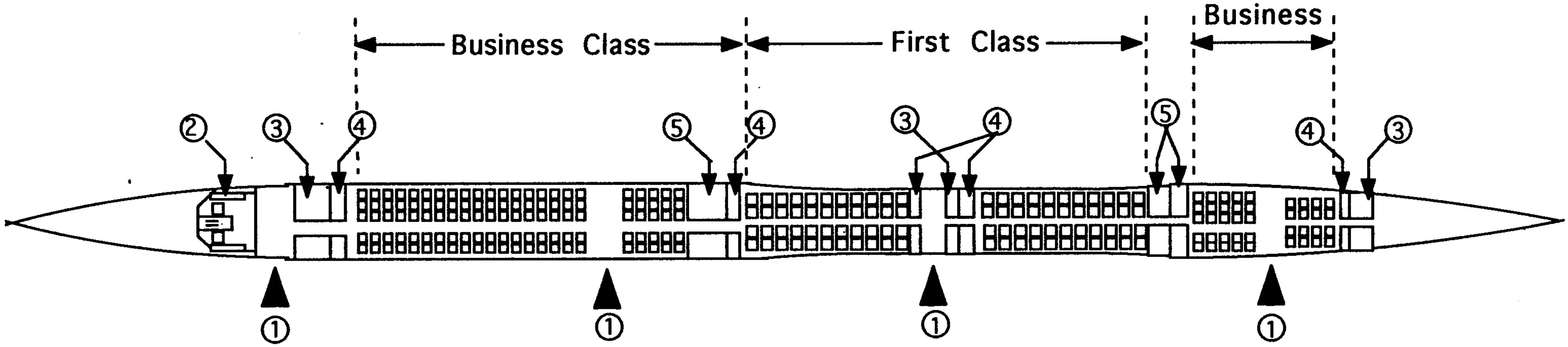
6.2 INTERNAL LAYOUT

The Trojan was configured to carry a 250 passenger load, with 65% business and 35% first class. Those numbers translate into 88 first and 162 business class seats. There is enough flexibility in the design of the aircraft to allow for additional seats to be added in either section, at the expense of reduced seat pitch.

An economy class was not designed into the Trojan because of economics. In order to attract the coach passengers, the fare ratio would have to be as close as possible to one. That is because a coach passenger is not as willing to pay extra for time savings as a first or business class passenger. Therefore, in order to keep the fare ratio low, there would have to be a large number of economy seats. Adding an economy class would require a much larger aircraft to accommodate the large number of coach seats.

As a result of the area ruling of the fuselage, the first class section will be placed in the center section of the aircraft, with business class seating both fore and aft of it.

Regular boarding is done through the port side door, closest to the front of the aircraft. That means that first class passengers will be required to walk through the business class section when they board. But, since the first class passengers will board well before the business passengers, they will have ample time to situate themselves. Figure 6.2 on the following page shows the Trojan's internal layout.



1 Entrance/Exit Doors
2 Cockpit
3 Lavatories
4 Closets
5 Gallies

Figure 6.2: Internal Layout for Trojan

Overall A/C Length	300 ft.	
Overall A/C Width	14 ft.	
Length/Width	21.5	
	1st Class	Bus. Class
Seats	88	162
Gallies	3	3
Lavatories	4	5
Closets	4	7

6.3 SEATING

First Class is a 2-2 arrangement, with a seat pitch of 38 inches and widths of 22 inches. British Airways Concorde first class seats have 34 inch pitch and Air Frances Concorde version has 32 inch pitch throughout their first classes. (Ref. 7) Slightly greater pitch than The Concorde is desired to increase overall spaciousness and comfort. Aisle height is 77 inches.

Business class is a 3-2 arrangement. Seat widths are 20 inches and have a pitch of 34 inches. Aisle height is 85 inches. Figure 6.3 shows the first and business class cross sections.

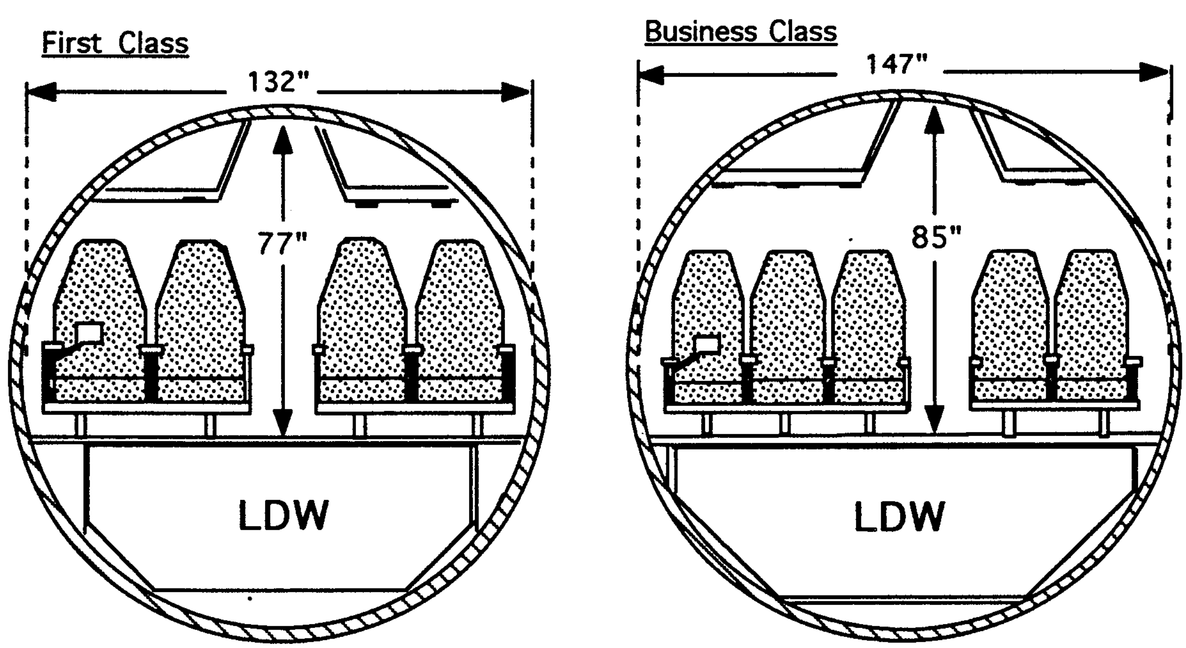


Figure 6.3: Trojan's Fuselage Cross Sections

There will be a single 19 inch aisle throughout the entire length of the aircraft. The 19 inch aisles are designed for easy passenger boarding and movement coupled with easier working conditions for flight attendants. (Ref. 8) There will be ample room for all existing meal and standard beverage carts currently in use.

Flight attendant seats are to be adjacent to door exits, as required by Federal Regulations, (Ref. 9) and they will be positioned so that they face the passengers. Seats are stowed upright and clear of exit paths. Seat pitch of 34 inches and width of 18 inches will be adequate for their purposes during take-off and landing.

6.4 BOARDING, EXIT, AND EGRESS DOORS

A single forward boarding door on the port side will be used for normal loading and unloading of passengers. A second door, sixty feet back from the first door, can serve as an alternate, or additional boarding door, should it be required. Existing boarding gates may will have to be extended in order to reach the second door, which is located 110 feet from the nose.

Two Type I doors (24" wide x 48" high) on each side of fuselage, two Type II doors (20" wide x 44" high) on each side of fuselage, plus one Type B door (additional 80 passenger exit doors) (Ref. 5) on each side of the fuselage satisfies FAR Part 25 requirements for 250 passenger civil transports. Furthermore, doors will be placed every sixty feet along the fuselage in order to satisfy the pending FAA rule.

6.5 CARGO CAPACITY

The overhead bins are placed directly above the seating area, on either side of the aisles, as pictured in Figure 6.3. They will provide for 3 ft^3 per first class passenger and 1.5 ft^3 per business class passenger, which are commensurate with current industry standards.(Ref. 8) Coat closets space is also provided and is 1.75 inch per first class passenger and 1.25 inch per business class passenger.

All baggage that is not carry-on will be stowed in LDW containers. LDWs were chosen because of the relatively limited belly cargo volume of the Trojan. Total belly cargo volume is 1000 ft^3. That amounts to 4 ft^3 per passenger. Therefore, total cargo capacity is 6.5 ft^3 and 6.0 ft^3 per first and business class passenger, respectively.

6.6 GALLEYS

There are a total of 3 galleys used to store and prepare food and beverages for both sections. The Trojan has 8 ft^3 and 4 ft^3 per first class and business class passenger, respectively. Although it is less than a Boeing 747, which has 10 ft^3 of galley space per first class passenger and 5ft^3 of galley space per business class passenger, the shorter amount of time spent in route on the aircraft must be taken into account.

6.7 LAVATORIES

A ratio of 15 first class passengers per lavatory and 30 business passengers per lavatory is the industry standard. (Ref. 12) The Trojan has a total of 9 lavatories, 5 in first class and 4 in business class. Sanitation considerations dictate that they be separate from galley areas. On the Trojan, no galleys were placed adjacent to lavatories.

6.8 ENTERTAINMENT SYSTEMS

The Trojan offers personal liquid crystal display systems for every passenger. Television sets are mounted in the seat arm rests and fold away when they are not in use, as shown in Figure 6.4.

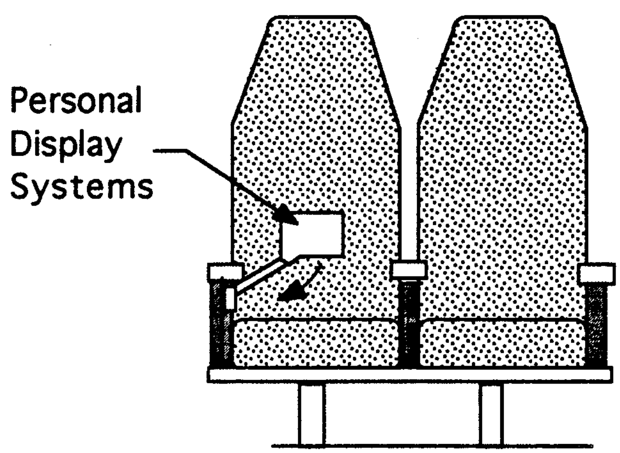


Figure 6.4: Trojan's Personal Entertainment Systems

The personal television will have different channels, showing movies, news, music videos, and views from outside of the aircraft.

Seat back televisions, which are currently in use on a Virgin Atlantic B- 747, were not used because of visibility problems caused by reclining passengers. Headphones will be used for audio reception of the T.V.s, which will eliminate any noise disturbances between passengers. One FAX machine and two telephones will be made available to both business and first classes.

6.9 COCKPIT SYSTEMS AND INSTRUMENTATION

The Trojan's cockpit is a modified layout of an Airbus 320 with the latest in systems technology (Fig 6.5). The control instrument labeled "I" will be used for an augmented vision display, which is needed upon landing due to the high angle of attack that limits the pilot's visibility. Due to this latest technology the crew of the Trojan can be minimized to two: The Captain and the First Officer. Two fold out observer seats are available in back of the crew.

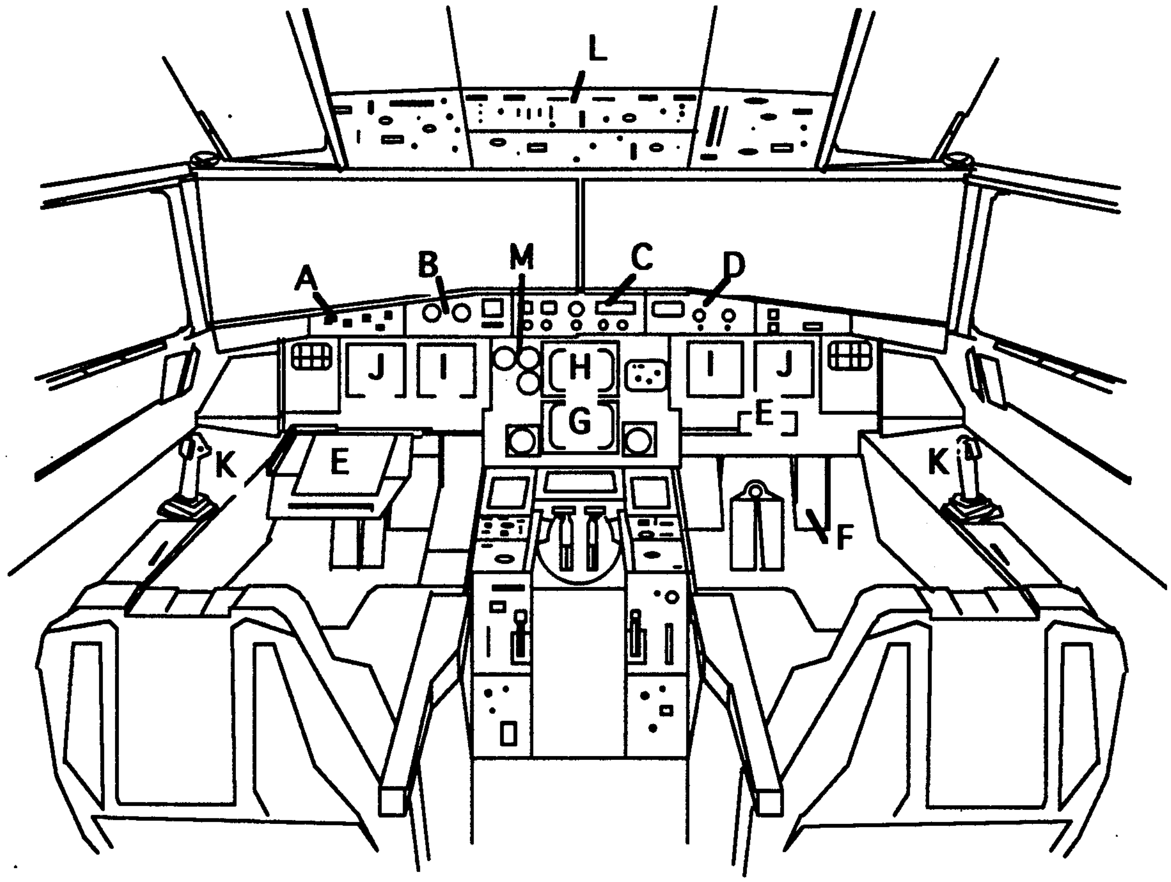


Figure 6.5: Cockpit Layout

A. Autoland
B. Electronic Flight Integration System (EFIS), Captain
C. Flight Control Unit Display
D. EFIS Controls, First Officer
E. Slideout Table
F. Rudder Pedal
G. Electronic Centralized Aircraft Monitoring (ECAM)
H. Engine and Warning Display
I.Artifical Landing and Navigation Display
J. Primary Flight Display
K. Sidestick Controller
L. Systems Control Panels
M. Standby Altimeter and Atitude Indicator

7.0 EMPENNAGE DESIGN

7.1 EMPENNAGE SIZING

Comparative studies of empennage configurations were examined (Ref 13). The results of this research indicated that a tailless design would minimize weight, cost and drag. Therefore, the term empennage, in the case of the Trojan, refers to the vertical stabilizer.

Preliminary studies involved a comparison of empennage designs from similar aircraft (Ref. 13). The vertical tail volume coefficients, surface area, and rudder to vertical tail surface area ratios for similar aircraft can be found in Table 7.1.

Table 7.1: Comparison of Supersonic Transport Vertical Tails

Aircraft Type	Vv	Sv (sq ft)	Sr/Sv
XB-70	0.034	468	0.75
Tu-144	0.081	648	0.19
Boeing SST	0.049	866	0.26
Concorde	0.080	477	0.24
Average	0.061	615	0.36

This comparison yielded an average volume coefficient of 0.061. The larger the moment arm the smaller the vertical tail can be. From a weight and balance analysis the maximum moment arm from the center of gravity to the vertical tail was determined to be 120 feet. These values were then used to solve for the surface area sizing, which was 677 sq. ft. A more accurate method, the X-Plot, further substantiated this result with a vertical tail surface area of 653 sq. ft. This X-Plot is represented in Figure 7.1. The vertical tail was designed not with a surface area of 653 sq. ft., but with 660 sq. ft. to allow for a margin of safety.

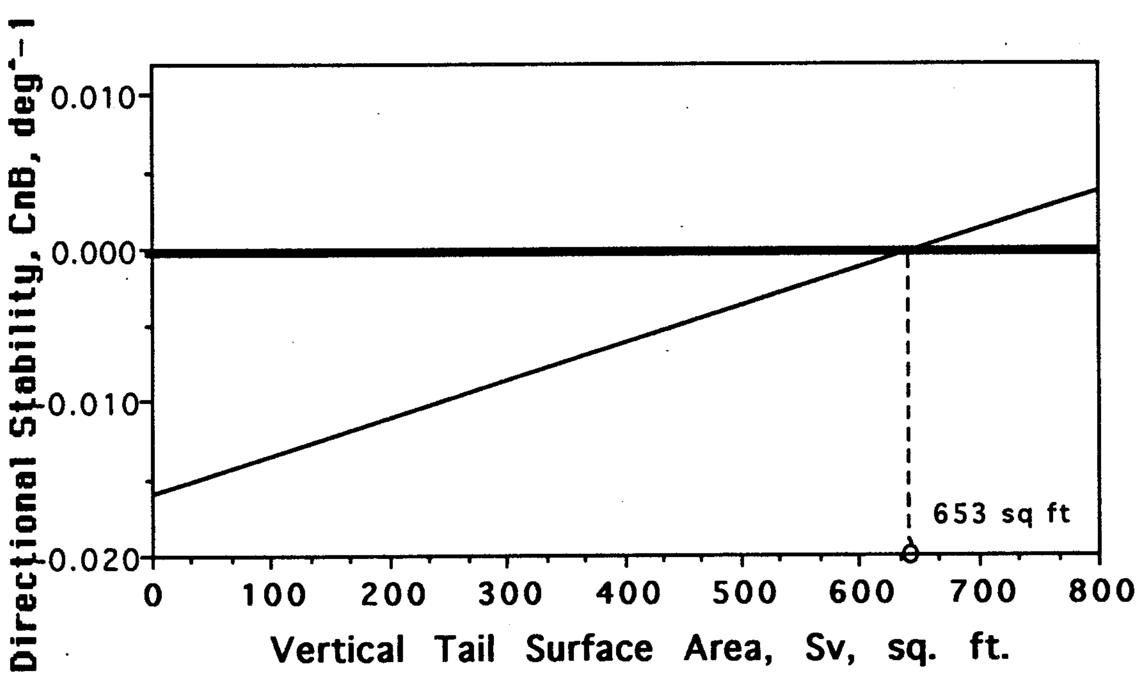


Figure 7.1: Vertical Tail X-Plot for the Trojan

7.2 EMPENNAGE PLANFORM

Several factors were involved in the selection of the vertical tail planform. This planform can be seen in Figure 7.2. A sweep angle of 65° was chosen so that the tail would be within the Mach cone and a subsonic airfoil could be used. A subsonic airfoil is critical for several reasons. First, subsonic airfoils are easier to construct and maintain. Second, subsonic airfoils offer a weight savings while increasing volume. But, more importantly, it is prudent to have the efficiency of the subsonic airfoil during the critical flight regimes of takeoff and landing. A NACA 0015 airfoil was chosen for its favorable performance characteristics.

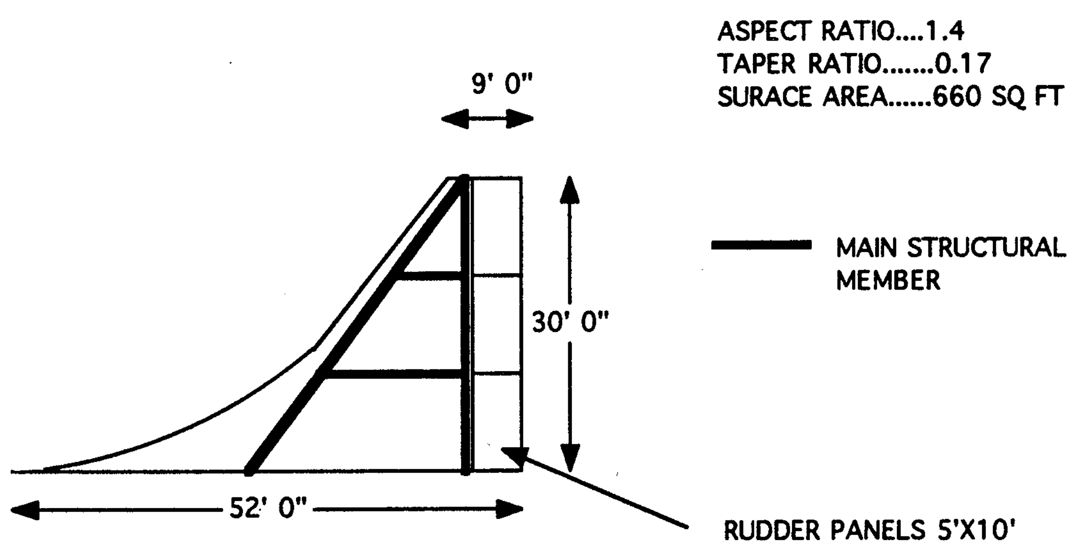


Figure 7.2: Vertical Tail Layout

The aspect ratio of the vertical tail is 1.4 and the taper ratio is 0.17. These low ratios allow for a tail that is not excessively tall. This makes the Trojan compatible with existing maintenance facilities. Low aspect and taper ratios also offer the benefits of weight savings and increased volume for structure and maintainability.

Initial comparative studies placed the ratio of the rudder surface area with respect to the vertical tail surface area at 0.36. An X-Plot found this to be liberal (see Appendix Part 13). The necessary ratio was only 0.23. While one 5'x10' panel can supply enough control power, the rudder has three 5'x10' panels for the purpose of redundancy. Each panel is signalled and actuated on completely independent circuits so that the Trojan can safely operate in the highly unlikely event of an electric or hydraulic failure.

8.0 PROPULSION SYSTEM

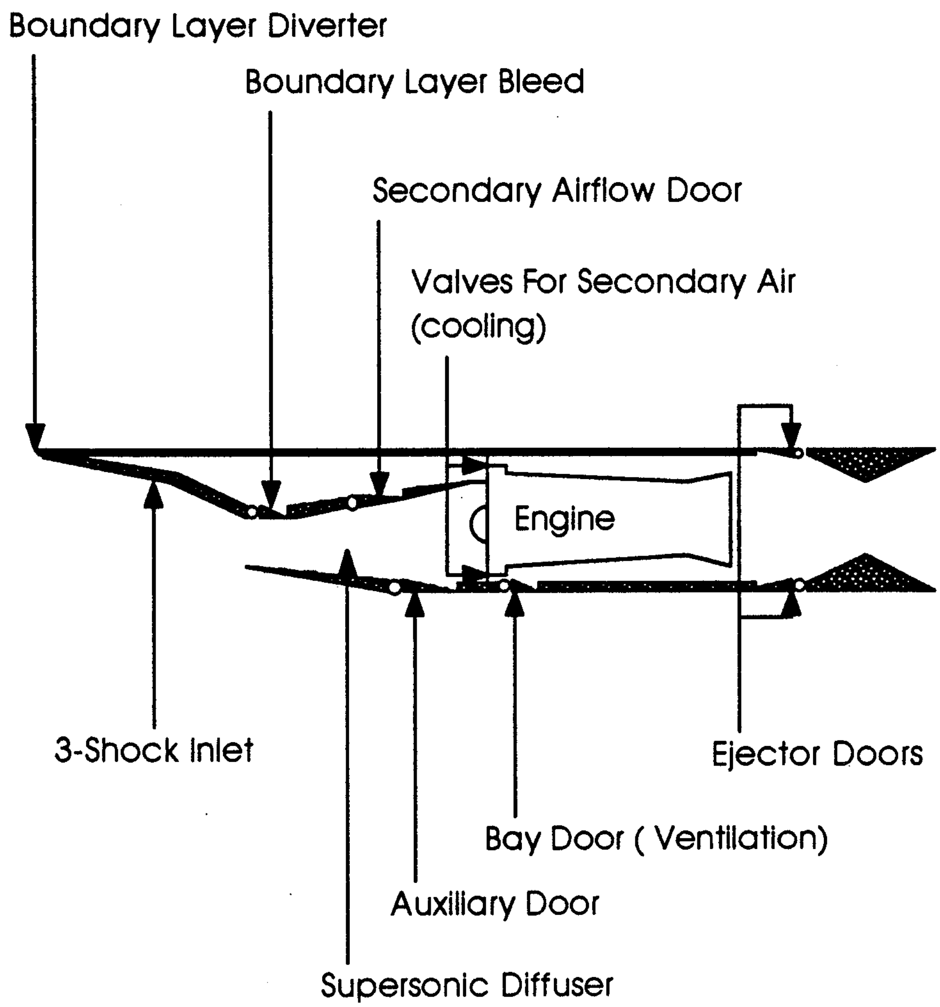
8.1 ENGINE SELECTION

There are many important considerations in the selection of a suitable propulsion system. The most determinant factors are: meeting the required thrust for take-off and cruise, having a low specific fuel consumption and having low noise and low emissions. The types of engines considered were straight turbofans, variable cycle turbofans, turbojets with and without afterburning, low bypass ratio turbofans and mixed flow turbofans. All of these engines were compared (see Table 8.1).

Table 8.1: Engine Comparison

ENGINE TYPE	SFC (CRUISE) [lb/lb-hr]	NET THRUST TAKE-OFF[lb]	AIRFLOW [lb/s]
RR Turbojet (Ref 14)	1.21	65,000	851
P&W TBE (Ref 15)	>1.2	49,640	600
NASA MIX (Ref 16)	1.14	53,000	788
Required for Trojan	1.14	73,000	944

The Mixed Flow Turbofan (Figure 8.1) from NASA (Ref. NASA) excelled in all of the critical areas. This engine uses mixed flow ejector nozzles to reduce noise by 19 dB, which is within Stage 3 noise requirements. The ejector nozzle doors open during take-off (Fig 8.2 on preceding page) to reduce the noise due to wind shear and jet exit velocity. The Mixed Flow Turbofan also meets necessary low NOx emissions requirements by using a GE/NASA clean combuster. It also had the lowest specific fuel consumption of all the engines considered. The required thrust was met by scaling up the existing NASA engine (Table 8.1).



Total Length = 49 [ft]
Engine Diameter = 8 [ft]
Bare Engine Length = 12 [ft]
Installed Engine Weight = 23,381 [lb]

Figure 8.1: Engine Layout for Trojan

8.2 INLET DESIGN/SELECTION

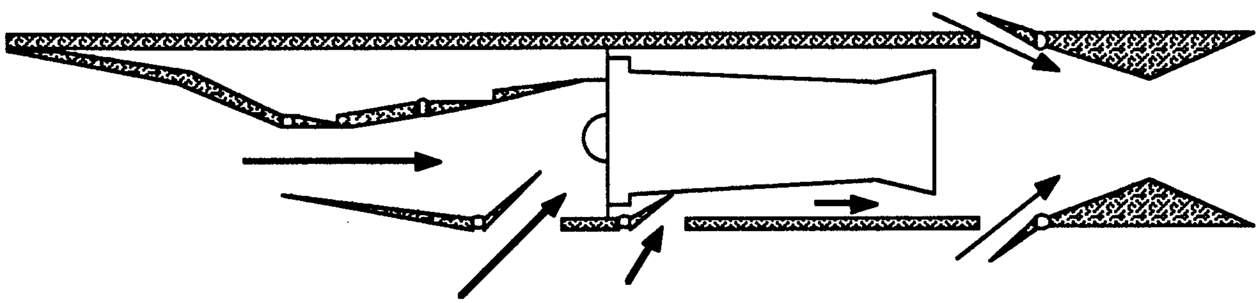
For a turbofan engine to be efficient, the air leaving the diffuser must be slowed down to Mach 0.4 - 0.5 so the tip speed of the compressor blades is below sonic relative to the incoming air. This reduction in velocity must be accomplished with as small a pressure loss as possible. The two main types of inlets that were considered were the spiked axisymmetric inlet and the 2-dimensional inlet.

The spiked inlet is typically lighter and has a slightly better pressure recovery than the 2-dimensional inlet, but has higher cowl drag and much more complicated mechanisms to produce the necessary variable geometry. For these reasons the 2-dimensional inlet will be used (Figure 8.1). Using Reference 2 and the cruise Mach number, it was determined that a 3-shock system will be used to minimize cost and complexity while maximizing pressure recovery. Figure 8.2 shows the intake geometry during take-off and supersonic cruise.

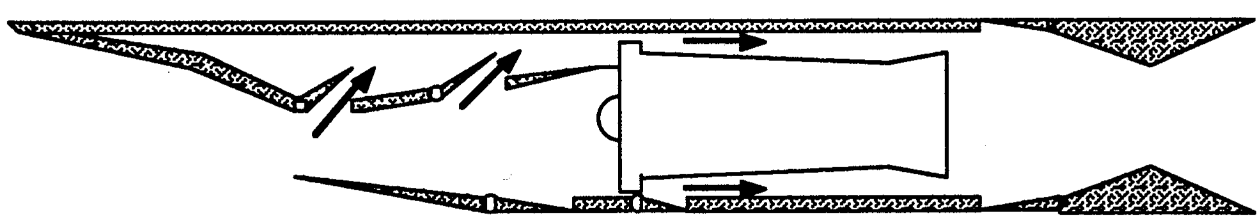
8.3 INLET LOCATION

Two types of engine installations were considered: the buried installation and the externally pod mounted installation. The buried installation is low in installed drag but the installation interrupts, and therefore, weakens the spars. Also, relatively poor accessibility and extra long tailpipes make the buried installation undesirable for the design. The externally pod mounted installation offers easy accessibility and is structurally more sound, therefore it was chosen.

Design Configurations



Take-off



Supersonic Cruise

Figure 8.2: Engine Operation Modes for Trojan

9.0 LANDING GEAR

9.1 GENERAL CONFIGURATION

The landing gear chosen for The Trojan is a retractable, tricycle configuration. The tricycle layout consists of three trucks for the main gear and a single truck for the nose gear. The three trucks of the main gear are in line, with the center truck directly below the fuselage along the centerline of the aircraft.

As shown in Figure 9.1 below, the two outboard trucks of the main gear have six tires each. The center truck of the main gear has four tires, and the nose gear two tires.

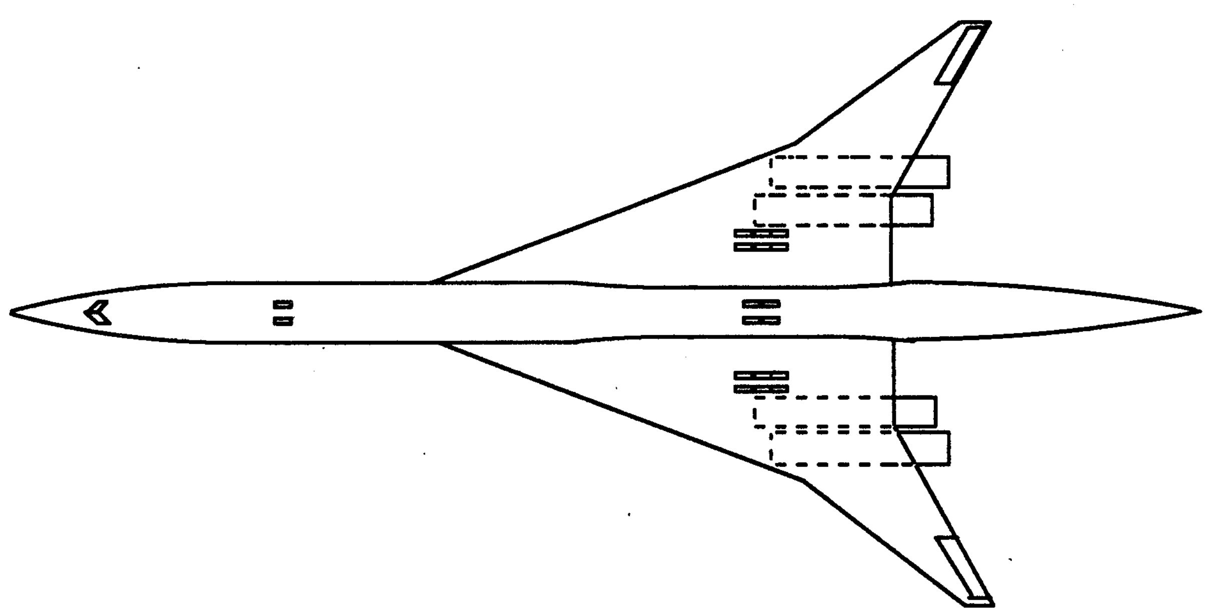


Figure 9.1: General Landing Gear Configuration for Trojan

The calculations, shown in the appendix, called for The Trojan, which is a 650,000 pound aircraft, to have 16 tires on the main gear. Because of the relatively limited stowage space, the design had to incorporate economy of space. As a result, this slightly unconventional design was developed.

The nose gear is a twin layout with a load classification number (LCN) of 42 and support 7% of the load. The main gear LCN is 65, as calculated from Reference 4, and supports 93% of the load. These LCNs are well below that of aircraft currently in service today with similar range and payload. For example, the MDC DC-10/10 has an LCN of 88.

The placement of the main gear is even with and slightly inboard of the inboard engine inlets, as shown in Figure 9.2 This configuration does not cause any flow obstructions into the the inlets, either while fully extended or during retraction.

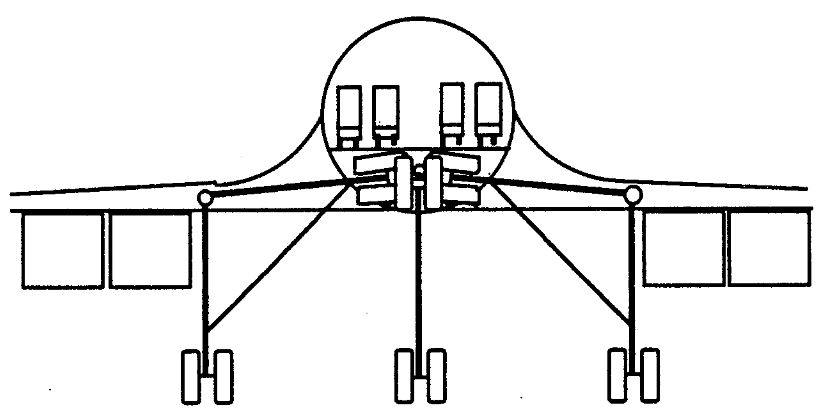


Figure 9.2: Trojan's Main Gear w/respect to engine Inlets

9.2 LONGITUDINAL TIPOVER CRITERIA

The placement of the main gear was determined by the longitudinal tip-over criteria, (Ref. 17) as shown in Figure 9.3.

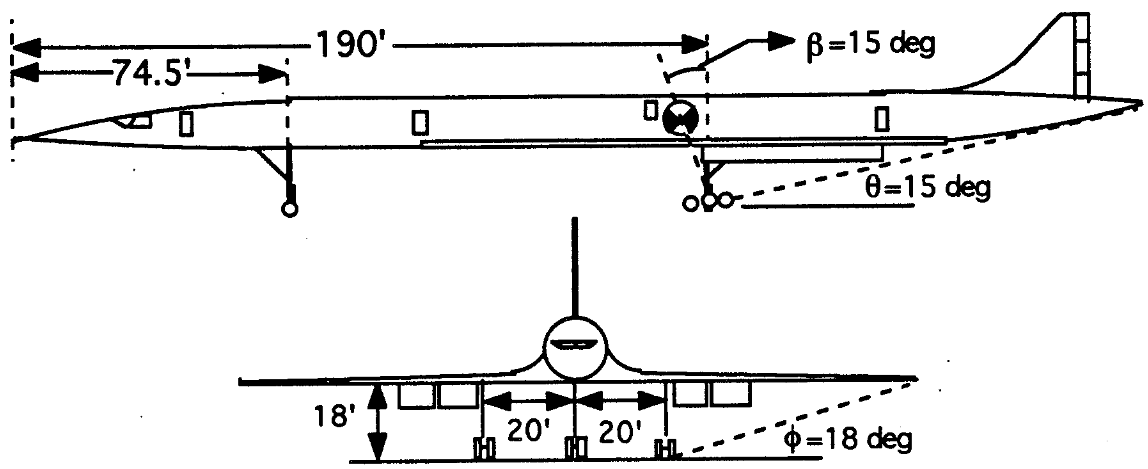


Figure 9.3: Longitudinal & Lateral Landing Gear Positions for Trojan

The height of the main gear was determined by the ground clearance requirements at take off. The angle θ, the longitudinal ground clearance angle, is 15 degrees for The Trojan. The angle of rotation for take-off is approximately 13 degrees. Beyond 15 degrees, engine nacelle clearance is the limiting factor.

9.3 LATERAL TIPOVER CRITERIA

There were two criteria that were used to determine the lateral placement of the main gear. They were the lateral tip-over requirements, and ease of retraction. The angle ψ is drawn between the most forward c.g. and a line perpendicular to the line drawn between the outer most wheel of the main gear and the nose gear. The lateral tip-over criterion requires that ψ be less than or equal to 55 degrees. For The Trojan, ψ = 46 degrees, as shown in Figure 9.4 (Ref. 17).

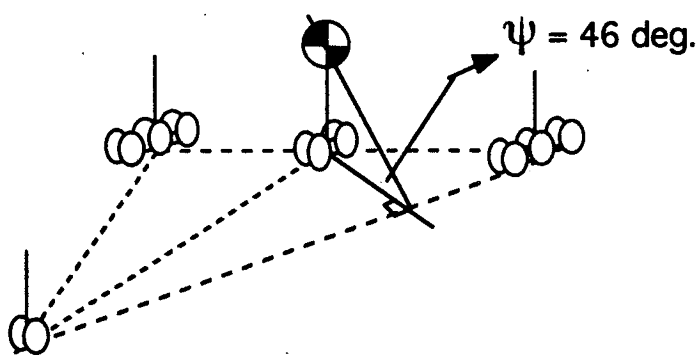


Figure 9.4: Later tip-over Requirement for Trojan

The lateral ground clearance requirement is also met by the main landing gear arrangement. As shown in Figure 9.2, the angle, ϕ, which is made between the outboard gear and the lowest part of the aircraft is 18 degrees. The requirement is for ϕ greater than 5 degrees (Ref. 17).

9.4 RETRACTION AND STOWAGE

In order to facilitate stowage of the outboard main gear, it was necessary to locate them a distance out from the centerline of the aircraft such that they could be fully retracted into the fuselage. Figure 9.5 shows how the main gear retract into the fuselage. When fully retrtacted, the main gear occupy a 28' x 11' x 5' volume.

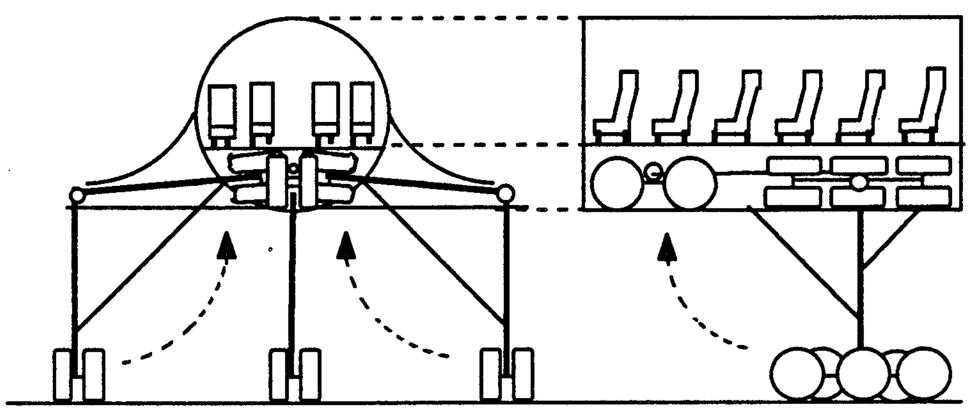


Figure 9.5: Main Gear Retraction for Trojan

The nose gear placement was determined by weight and balance considerations. The retraction of the nose gear, as shown in Figure 9.6, is forward with a horizontal slot. There was ample room for stowage, therefore no special provisions were made for retraction and stowage. The nose gear occupy a 20' x 9' x 4.5' volume, when fully retracted.

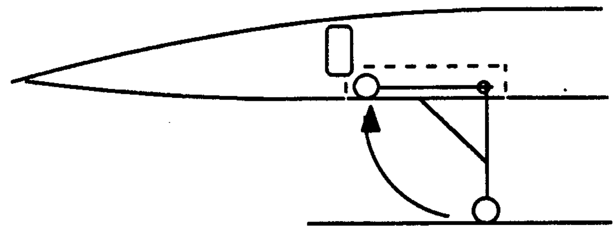


Figure 9.6: Trojan Nose Gear Retraction

Table 9.1, below, summarizes some of the specifications (Ref. 4) pertaining to both the nose, and the main landing gear.

Table 9.1: Trojan Landing Gear Data

	Nose Gear	Main gear
Tire Size	46" x 16"	46" x 16"
Type	VII	VII
#of Tires	2	16
Tire(psi)	190	206
#of Struts	1	3
Rake	no	no
Trail	no	no

The nose and the main landing gear configurations are shown in Figure 9.7, on the following page.

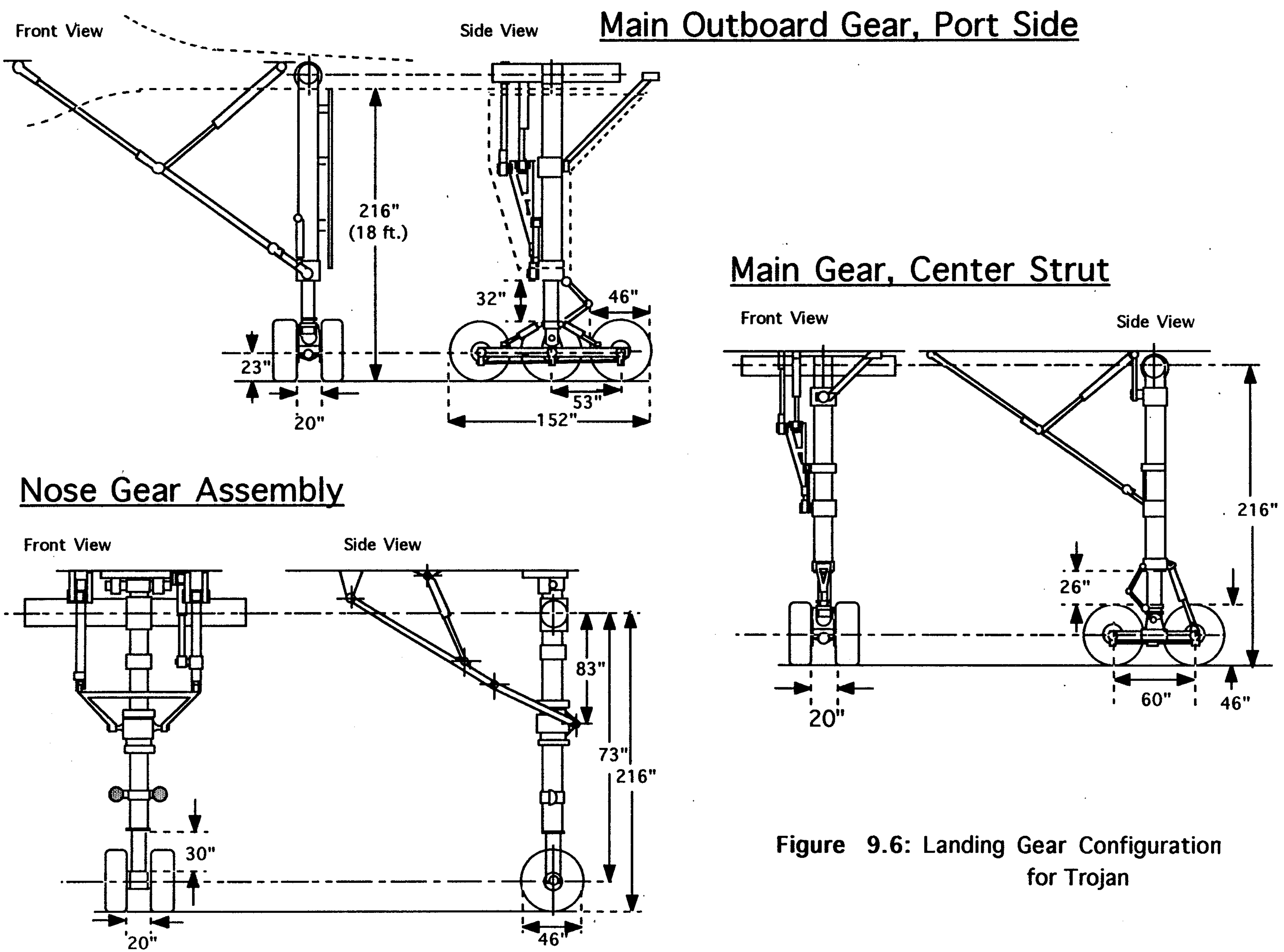


Figure 9.6: Landing Gear Configuration for Trojan

10.0 STRUCTURES

10.1 V-n DIAGRAM

The V-n diagram (Figure 10.1) shows the Trojan's flight envelope which is constrained by the maximum structural and aerodynamic load factors. The positive and negative limit load factors are +2.5 and -1.0 respectively. The various speeds to which the Trojan's structures are designed and shown in Figure10.1. The limiting case for the Trojan was determined to be manuver.

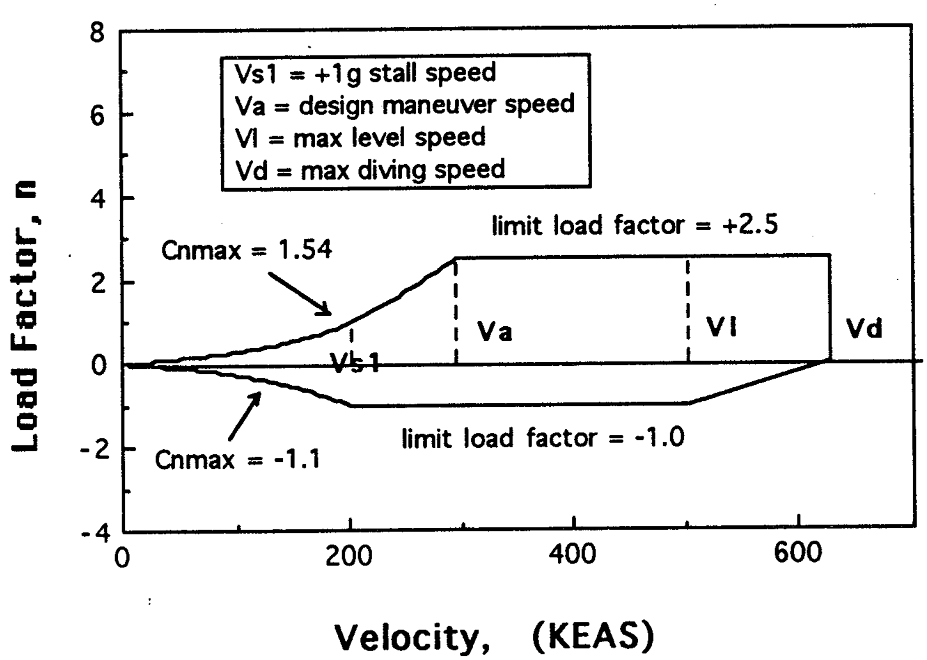


Figure 10.1: V-n Diagram for Trojan

10.2 FUSELAGE LAYOUT

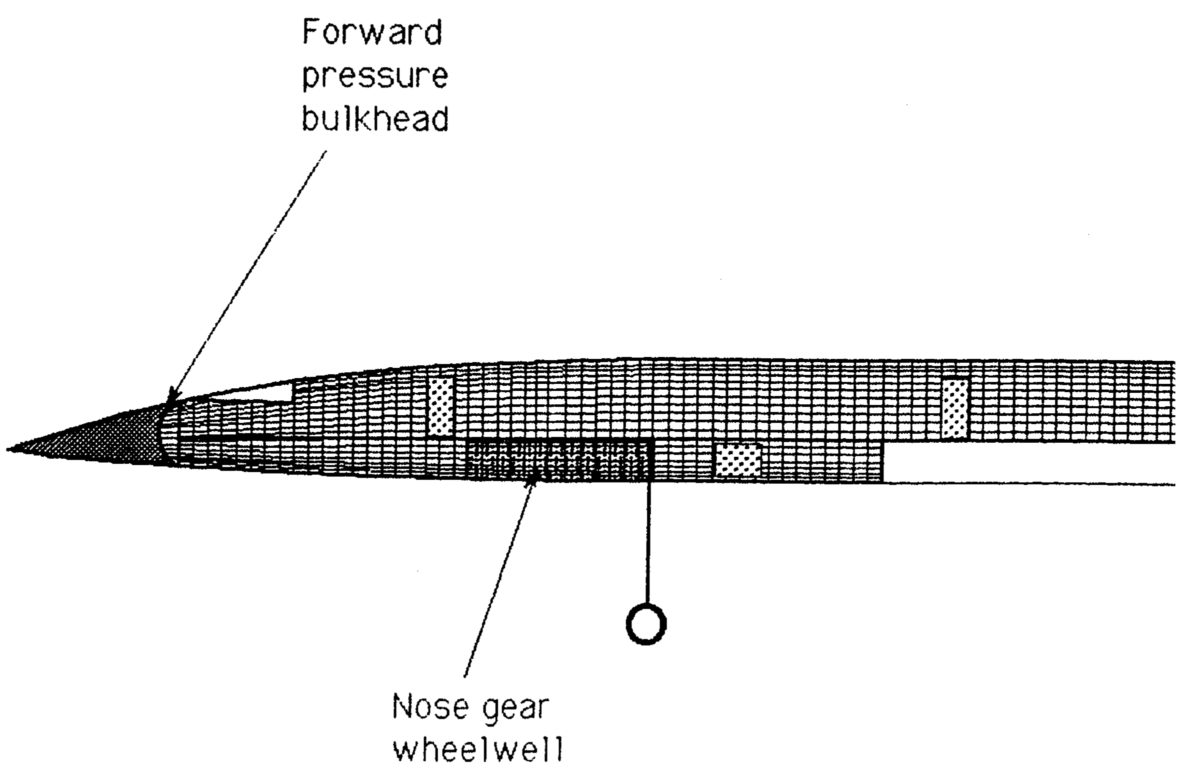
The Trojan's fuselage is a conventional semi-monocoque structure, similar to that of many subsonic transports, such as the Boeing 747. The Trojan has frames connected by longerons, which are covered by a skin, as shown in Figure 10.2 on the next page. The frame spacing is 20 inches and the longeron spacing is approximately 11 inches. These spacings are typical of many large transports (Ref. 11). There are hemispherical pressure bulkheads at each end of the fuselage. Hemispherical bulkheads were chosen because of their lighter weight construction, compared to flat pressure bulkheads. Since the Trojan cruises 25,000 feet higher than most subsonic aircraft, the cabin pressurization is much higher. Because of the structural weight penalty incurred by this higher pressurization, passenger windows are absent on the Trojan. Besides the weight penalty, the windows were eliminated due to blending of the wing and fuselage.

10.3 VERTICAL TAIL LAYOUT

The vertical tail of the Trojan is a multi-spar structural layout with three vertical spars and two longitudinal spars. As shown in Figure 10.2, the ribs are arranged vertically and have a spacing of 48 inches. Such a large rib spacing is facilitated by a composite skin that will be discussed in Section 10.5. Vertical tail spars are attached to the fuselage at enlarged fuselage frame cross sections.

These frames transmit the loads to the fuselage skin. The rudder is a three panel fail safe design.

FOLDOUT FRAME 1



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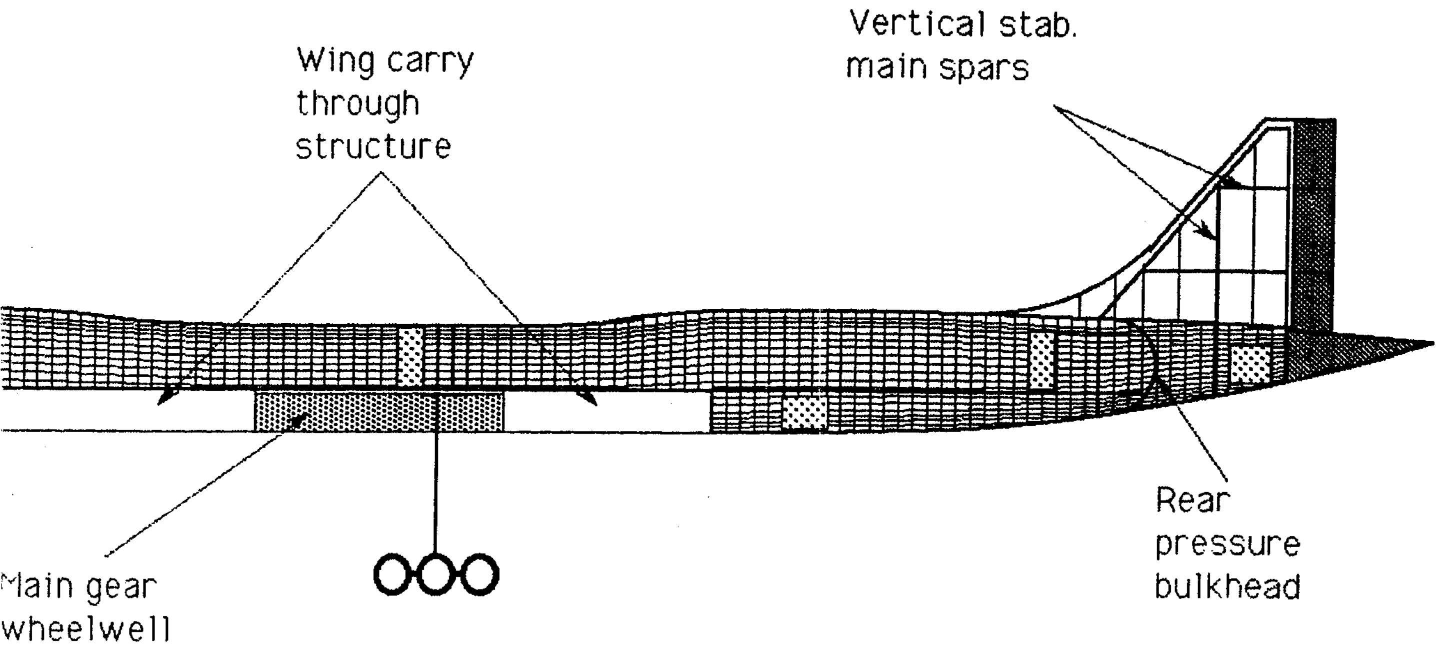


e10.2: Structural side view for Trojan

10.4 WING LAYOUT

The structural layout for the wing is shown in Figure 10.4. The wing is a multi-spar design with four primary spars. Three are transverse and one is longitudinal. There are five secondary spars, two are longitudinal, two are in the wing tip, and one is lateral. The forward two primary spars are located just fore and aft of the wheel well. These spars distribute the load of the wing where there is no carry through structure. Additionally, these spars carry the landing gear loads passed from the primary longitudinal spars. The aft primary spar carries the engine mountings and the inboard flight controls. Due to the small aspect ratio and large chord, the ribs were located transversely. This rib arrangement is both lighter and stronger. An example of an inboard cross section is shown in Figure 10.3. Wing tips on the Trojan are of a more conventional design. The tips are a two spar torque box with perpendicular ribs. The forward and rear spars are at 20% and 67% span, respectively. Rib spacing throughout the wing is 24 inches. As shown in Figure 10.4, the center main landing gear loads are given to the fuselage through enlarged frames at that location.

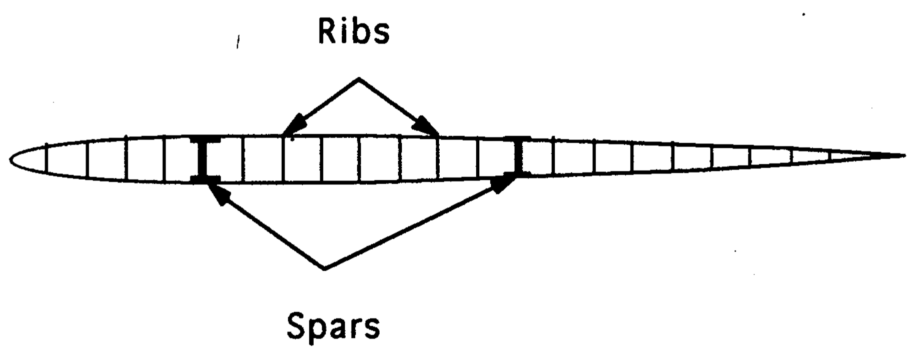


Figure 10.3: Inboard wing cross section for Trojan

FOLDOUT FRAME 1

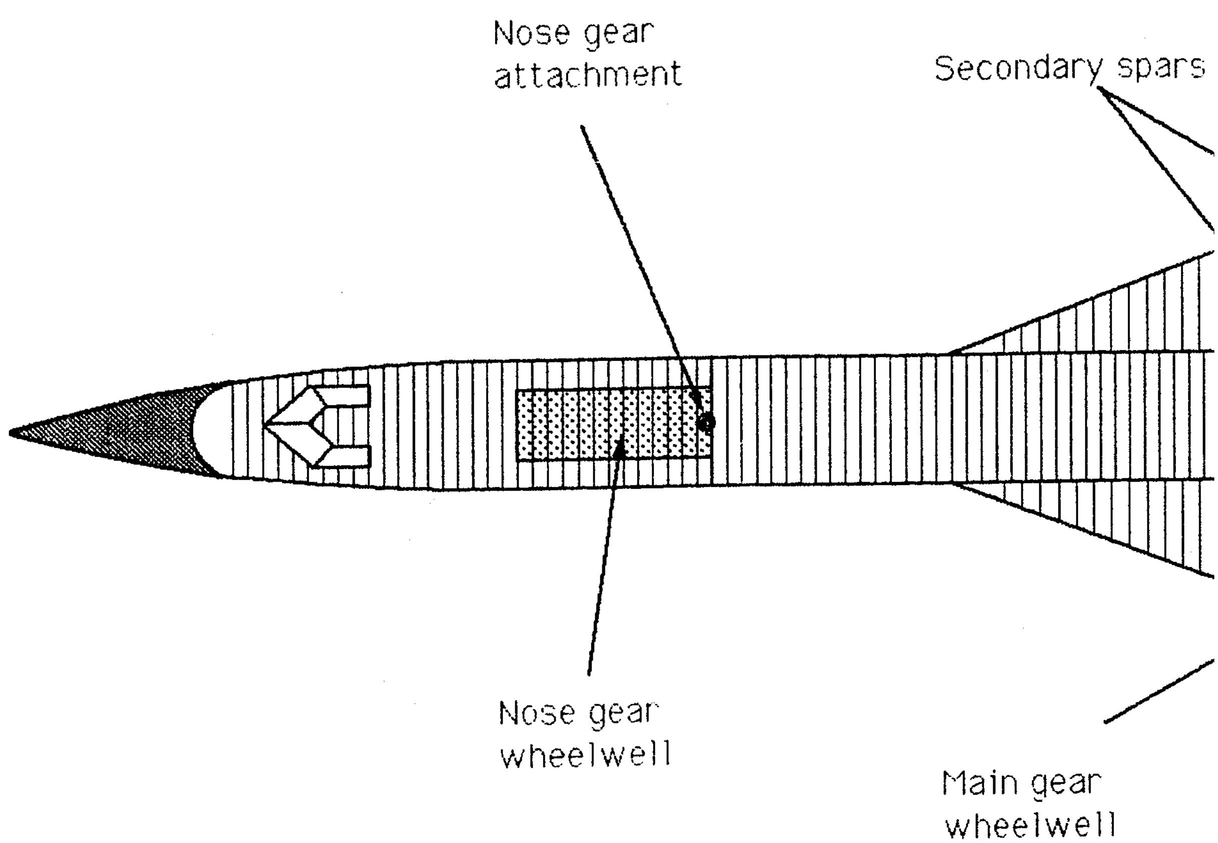
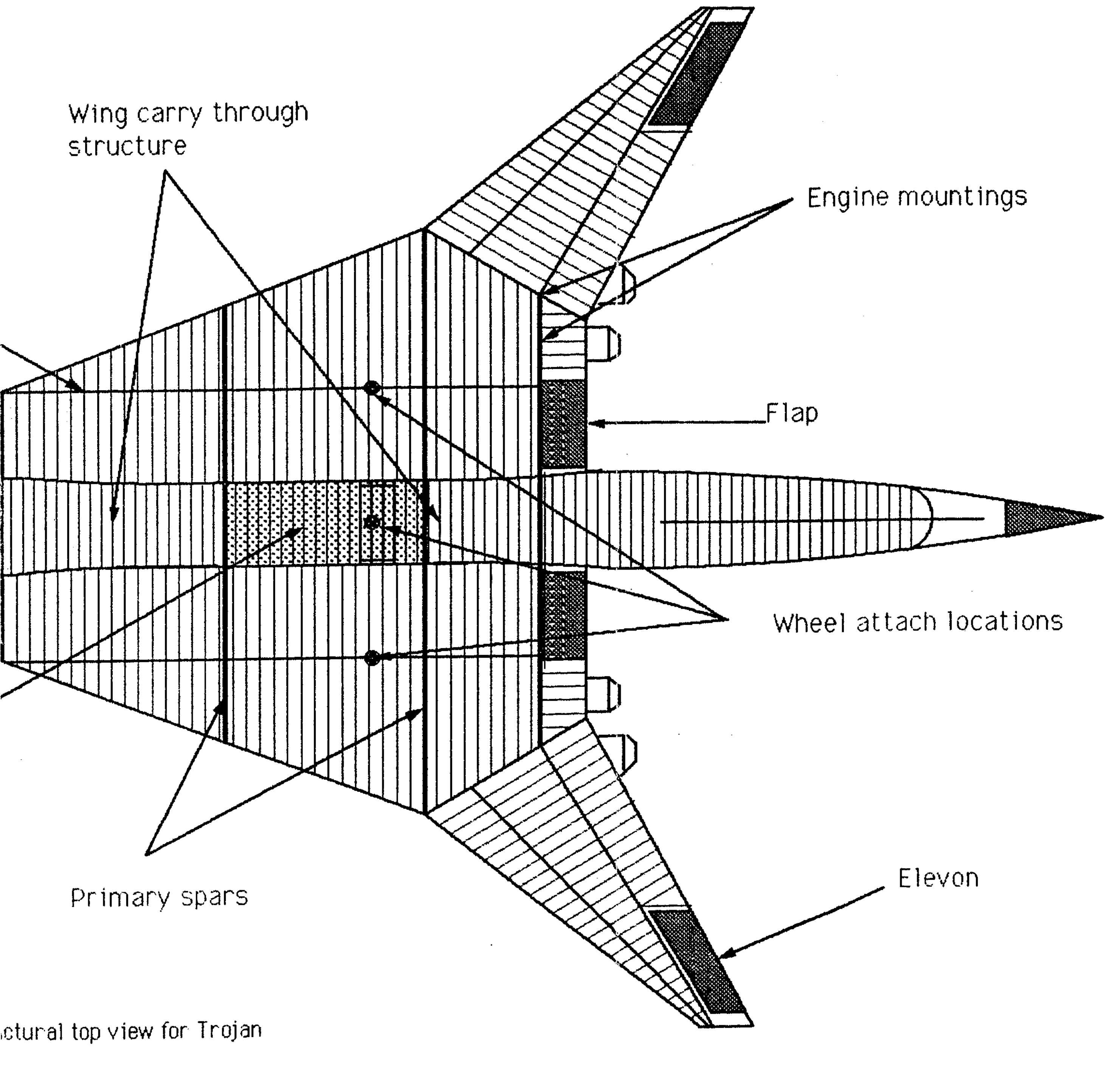


Figure 10.4: S

FOLDOUT FRAME 2.



ctural top view for Trojan

10.5 MATERIALS

In the interest of cost and weight savings, the majority of the Trojans' structure is composed of aluminum. Excluding stagnation points, which are made of titanium, the maximum temperature on the structure is 230 deg. F (Ref. 13). The lower wing and fuselage skins are composed of 7075-T6 aluminum, which has superior strength characteristics in tension (Ref. 6). 7075-T6 is also used for the spars. The frames, ribs, bulkheads, and longerons are made of 2024-T4 aluminum, which is light weight and fatigue resistant (Ref. 11).

Graphite epoxy was selected for the skins of the vertical stabilizer and wing upper surface, as was done on the McDonnell Douglas F-18 Hornet (Ref. 11). A major benefit of graphite skin is the rib spacing can be increased, resulting in lighter construction and a lower manufacturing cost. Graphite epoxy offers a 25% weight saving over aluminum (Ref. 6). The control surfaces are also constructed of graphite epoxy, as shown in Figure 10.5.

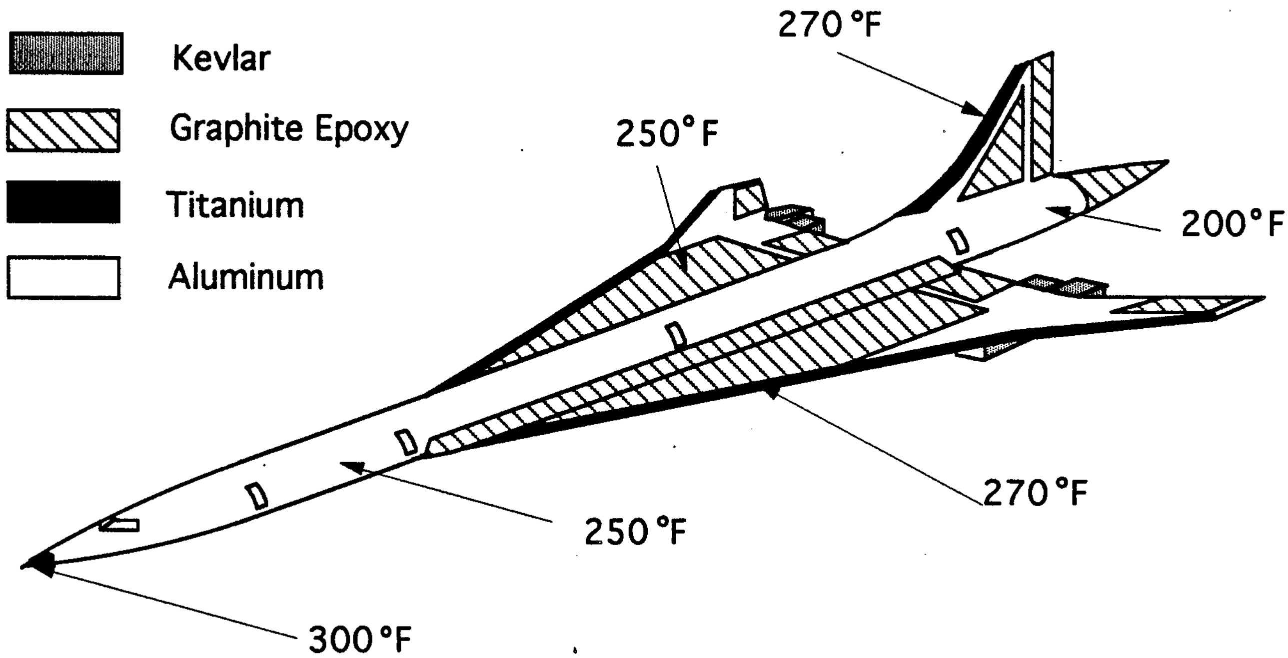


Figure 10.5: Material Distribution

At supersonic speeds high temperatures occur at stagnation points, such as the nose and the leading edges (Ref. 6). Because of the high temperatures, the Trojan has a titanium nose cone as well as titanium leading edges on the wing and vertical stabilizer.

Various other materials are used throughout the rest of the aircraft. The high loads imposed on the landing gear require it be constructed of high strength steel. Fiberglass is used for the floor main deck panels as well as for overhead bin assemblies. Kevlar is used to encase the engines because of its high strength capabilities. High strength is required in case of an unconstrained compressor failure.

11.0 PERFORMANCE

11.1 DRAG ANALYSIS

A study of the drag characteristics of the Trojan was conducted using the component buildup method (Ref.2). This method involved the determination of the coefficient of drag for each major component of the aircraft. These values were then summed and the drag polars evaluated. The drag polars are depicted in Figures 11.1 and 11.2.

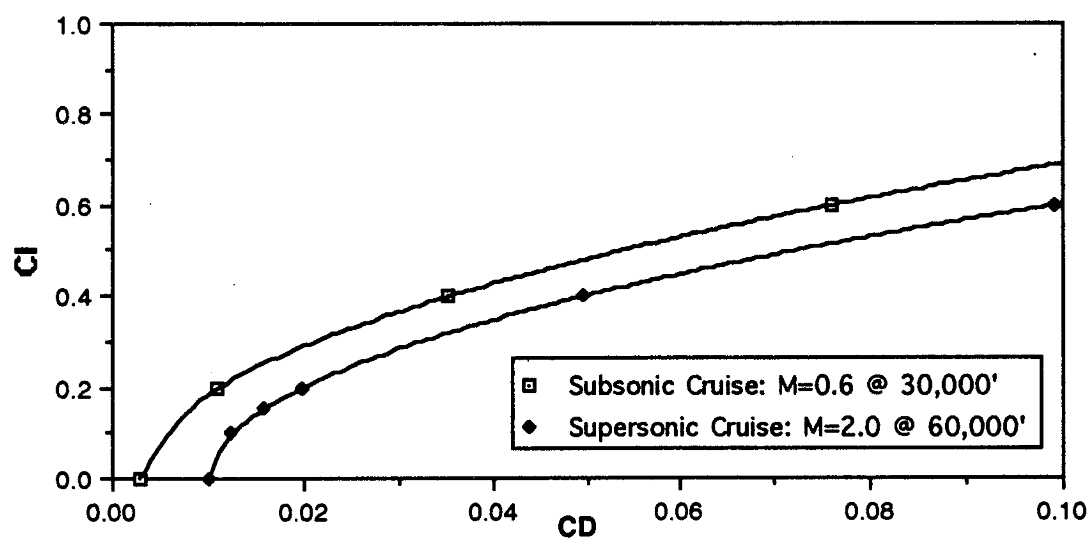


Figure 11.1: Subsonic and Supersonic Cruise Drag Polars

Figure 11.1 shows the drag polars for the subsonic and supersonic cruise configurations. This graph shows that the zero lift drag coefficient for the subsonic case is 0.002, and 0.099 for the supersonic case. The subsonic zero lift drag coefficient is consistently higher than in the supersonic case. The drag analysis also resulted in an L/D ratio of 18.2 and 10.8 for the subsonic and supersonic cases, respectively. These are typical values for an aircraft of this type (Ref. 19).

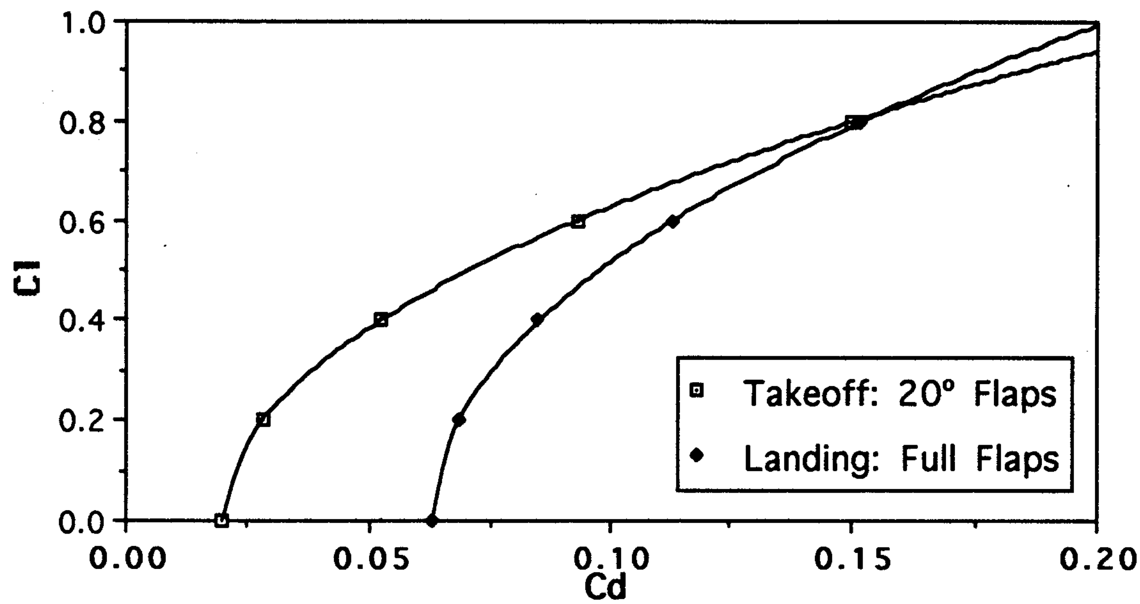


Figure 11.2: Take-off and Landing Drag Polars

Figure 11.2 shows the drag polars for the take-off and landing configurations. The zero lift drag coefficients for take-off and landing are 0.020 and 0.068, respectively. The great difference in these two values is attributed to full flaps in the landing configuration.

11.2 TAKE-OFF

The take-off field length was calculated to be 9,825 feet, which is under the restricting 10,000 foot take-off distance requirement, enabling compatibility with existing international airports. The Trojan will lift-off at 185 knots, with the triple slotted flaps set at 20 degrees aiding in generating a lift coefficient of 0.65. The aircraft rotation angle upon take-off is 13 degrees and must not exceed 15 degrees due to structural limitations. Figure 11.3 illustrates the take-off performance.

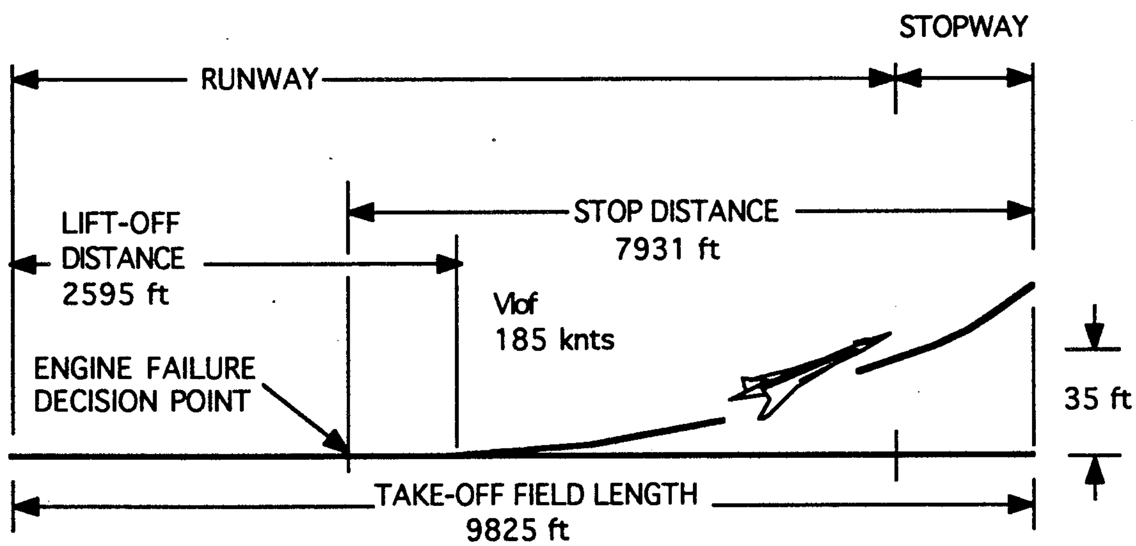


Figure 11.3: Take-off Performance for the Trojan

11.3 LANDING

The Trojan begins its landing approach at a minimum of 50 ft. above any object in its flight path at a velocity of approximately 218 knots. The Trojan then reduces this velocity with 30 degrees of triple slotted flaps, to flare and touchdown at 193 knots. The ground roll upon landing , with the instant application of spoilers and antilocking brakes, was determined to be only 5,400 ft. No reverse thrust is required to achieve this landing distance which is a favorable characteristic. For one, reverse thrust may not be employed during F.A.A. landing certification and two, reverse thrust is an extremly loud option. Figure 11.4 illustrates the Trojan's landing performance.

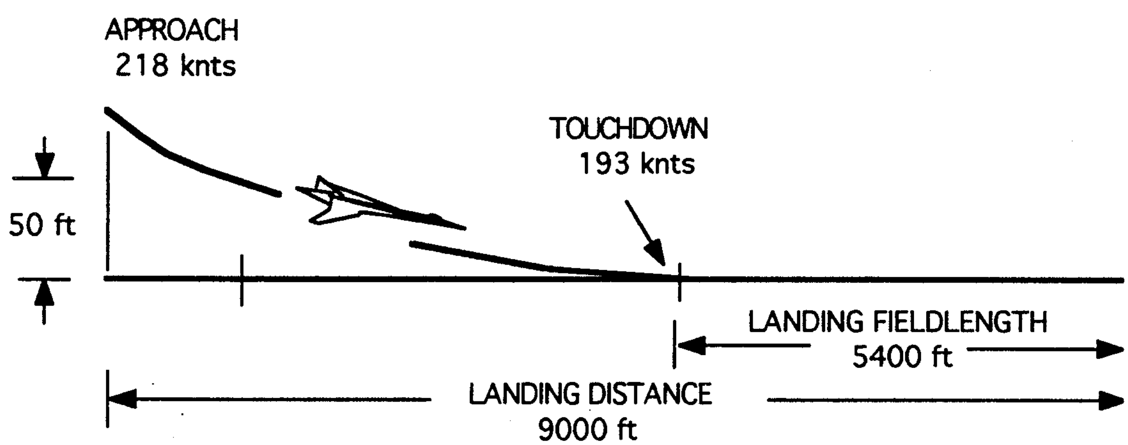


Figure 11.4: Landing Performance of the Trojan

12.0 CENTER OF GRAVITY AND MOMENT OF INERTIA

12.1 CENTER OF GRAVITY ANALYSIS

The center of gravity (CG) of the Trojan was found by dividing the aircraft into major components (Appendix 12). The weight and center of gravity of each of these components were found. Whenever possible, actual component weights were used (for instance, payload weight). Otherwise, the equations of Reference 5 were used to find the component weights. The moments of each of these components around the datum were then summed. The datum for the Trojan was set 10 feet in front of the nose, 10 feet below the ground and along the center line in the y direction to allow for growth in the design process. The total of the moments was divided by the total weight for numerous loading combinations of empty weight, fuel, passengers, baggage, crew, and trapped fuel and oil. This analysis gave 37 different CG locations corresponding to the different loading situations.

From the center of gravities generated, a CG excursion diagram was made (Fig. 12.1). This diagram shows CG location in the x direction for two different loading sequences. The first sequence is: start with empty weight, add trapped fuel and oil plus crew, add fuel, and then add passengers and baggage. The second sequence is: start with empty weight, add trapped fuel and oil plus crew, add passengers and baggage, and then add fuel. These two loading sequences were selected due to the fact that they would be most useful in determining if there was a loading sequence problem. No loading sequence problem is known to exist or is anticipated.

The CG excursion diagram also shows the max CG shift for the Trojan of 12.8 feet or 0.096% of root chord.

Table 12.1 shows the maximum and minimum CG location for the x and z direction. The center of gravities for the y direction are all zero for every loading situation. Table 12.1 also shows the maximum CGx travel in feet.

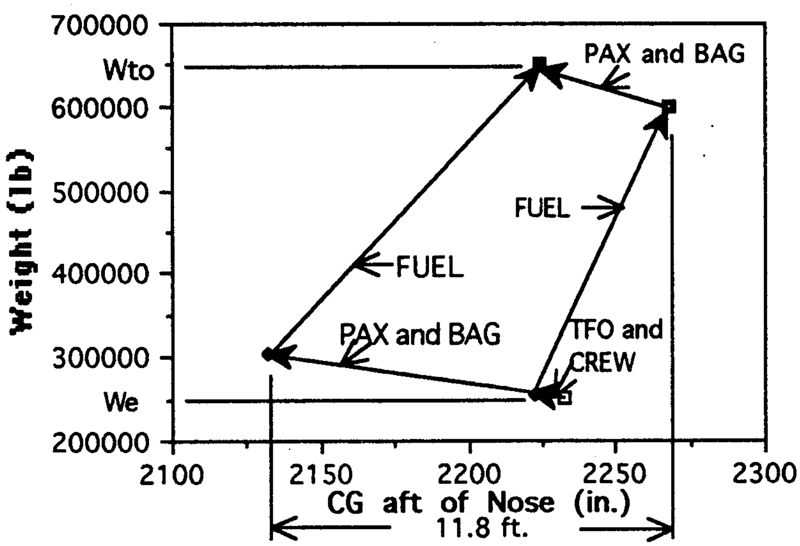


Figure 12.1: CG Excursion

Table 12.1: CG Analysis Results

Maximum forward CGx location (passengers, baggage, and crew loaded)	188
Maximum rear CGx location (fuel and trapped fuel and oil loaded)	199
Maximum CGz location (passengers, fuel, trapped fuel and oil, and crew loaded)	-19.1
Minimum CGz location (baggage and crew loaded)	-1.15
Maximum CGx travel (from passengers, trapped fuel and oil, crew, and baggage loaded to We)	11.8
(all units are feet)	

12.2 MOMENTS OF INERTIA

The moments of inertia for the Trojan were determined for three different loading situations: 1) weight at takeoff, 2) empty weight, and 3) takeoff weight minus fuel weight. The moment arm of each component is the distance from the center of gravity location for the loading situation being investigated and the component's own CG location. Values for the moments of inertia for the three loading configuration are presented in Table 12.2.

Table 12.2: Moments of Inertia

	We	Wto	Wnf
Ixx	7.04E+06	2.83E+06	5.84E+06
Iyy	2.40E+07	2.41E+07	2.63E+07
Izz	1.70E+07	2.13E+07	2.04E+07
Ixy	0	0	0
Ixz	-5.10E+05	-3.90E+05	-4.29E+05
Iyz	0	0	0
	(units are slug-ft^2)		

13.0 STABILITY AND CONTROL

This section summarizes the analysis of stability and control characteristics for the Trojan. Static and dynamic stability were examined, which resulted in the need of a Stability Augmentation System (SAS). Estimates of subsonic and supersonic rigid airplane derivatives were calculated and are tabulated. Verification of trim capability throughout the flight envelope is provided with trim diagrams. Handling qualities required the application of control theory and closed-loop gain requirements to meet the desired Level 1 flying qualities. An overview of the proposed control system is illustrated and discussed.

13.1 STATIC AND DYNAMIC STABILITY

The Trojan was designed to be inherently unstable, to provide a savings in control surface and vertical tail areas as well as a weight savings. These savings translate to a reduction in drag and an overall more efficient aircraft. Through the static and dynamic analysis, the Trojan proved to be an unstable aircraft in the subsonic flight regime. The level of longitudinal stability varies from a maximum unstable value of -7% in subsonic flight to a maximum +4% stable value in supersonic cruise. This inherent instability naturally requires an artificial stability augmentation system, which is discussed in detail in the following sections.

13.2 STABILITY DERIVATIVES

The stability and control derivatives for the Trojan have been evaluated for subsonic and supersonic flight using the methods of Reference 19 and Reference 20 respectively. Table 13.1 defines the flight conditions, geometry and inertias, and steady state coefficients for the stability analysis. The corresponding Trojan stability derivatives are listed in Table 13.2.

Throughout the remainder of the discussion, these flight conditions are referenced as Flight Condition 1, 2, and 3. These flight regimes were chosen for analysis to cover the broad spectrum of flight from slow, gear down, flaps extended, landing configuration to the supersonic cruise configuration. Stability of the Trojan significantly changes in these flight conditions due to center of gravity and aerodynamic center shifts. These differences are analytically displayed in the sections to follow.

Table 13.1 Flight Conditions of Stability Analysis

FLIGHT CONDITION	1	2	3
	POWER APPROACH	SUBSONIC FLIGHT	SUPERSONIC CRUISE
ALTITUDE (ft.)	sea level	20000	60000
AIR DENSITY (slugs/ft^3)	0.002389	0.001268	0.000224
SPEED (Mach)	0.24	0.60	2.00
CENTER OF GRAVITY (Xcg)	0.56	0.63	0.60
INITIAL ATTITUDE (deg.)	6.0	3.0	0.8
GEOMETRY AND INERTIAS			
WING AREA (ft^2)	8652	8652	8652
WING SPAN(ft.)	154	154	154
WING MEAN GEOMETRIC CHORD (ft.)	92.5	92.5	92.5
WEIGHT (lbs.)	342800	618500	618500
Ixx (slug ft^2)	3245400	3247600	3247600
Iyy (slug ft^2)	24042500	24097400	24097400
Izz (slug ft^2)	17423200	20842700	20842700
Ixz (slug ft^2)	-410600	-475100	-475100
STEADY STATE COEFFICIENTS			
CL	0.46	0.29	0.17
CD	0.092	0.020	0.016
CTX	-0.092	-0.020	-0.016
CM	0	0	0
CMT	0	0	0

The following stability derivatives are only analytical estimations; more accurate values may be acquired with wind tunnel testing.

Table 13.2: Longitudinal and Lateral Derivatives

LONGITUDINAL DERIVATIVES	1	2	3
Cm u	0	-0.0331	0.0096
Cm alpha	0.0374	0.112	-0.0791
Cm alpha dot	-0.065	-0.058	-0.600
Cm q	-0.00352	-0.0106	0.00704
Cm tu	0	0	0
Cm t alpha	0	0	0
CL u	0.0246	0.135	-0.237
CL alpha	0.108	0.131	2.31
CL alpha dot	0.065	0.058	0.060
CL q	0.090	0.107	0.056
CD alpha	0.23	0.28	0.24
CD u	0	0	-0.00216
CT xu	0	0	0
CL ∂e	0.0143	0.0152	0.0161
CD ∂e	0.00454	0.002859	0.001676
Cm ∂e	-0.0327	-0.0319	0.0229

LATERAL-DIRECTIONAL DERIVATIVES			
Cl beta	-0.1184	-0.1091	-0.09582
Cl p	-0.0624	-0.0559	-0.0492
Cl r	0.00959	0.00598	0.00957
Cl ∂A	0.0504	0.0316	0.0186
Cl ∂R	0.0000627	0.0000921	0.00011
Cn beta	0.03624	0.002109	0.05872
Cn p	0.00967	-0.00912	0.01433
Cn r	-0.07917	-0.08873	-0.09287
Cn ∂A	-0.00753	-0.00298	-0.00103
Cn ∂R	-0.00356	-0.00347	-0.00311
Cy beta	-0.0742	-0.0683	-0.0668
Cy p	0	0	0
Cy r	0.00487	0.00491	0.00492
Cy ∂A	0	0	0
Cy ∂R	0.0426	0.00384	0.01798

13.3 TRIM

The Trojan uses elevons to provide trim and pitch control due to the absence of a horizontal tail. Trim diagrams are provided for gear down and gear up take-off configurations, subsonic flight, and supersonic cruise. Figure 13.1 illustrates that the elevon control surface deflections are within control power capabilities and that the required angles of attack are below aircraft stall, both of which are criteria for acceptability.

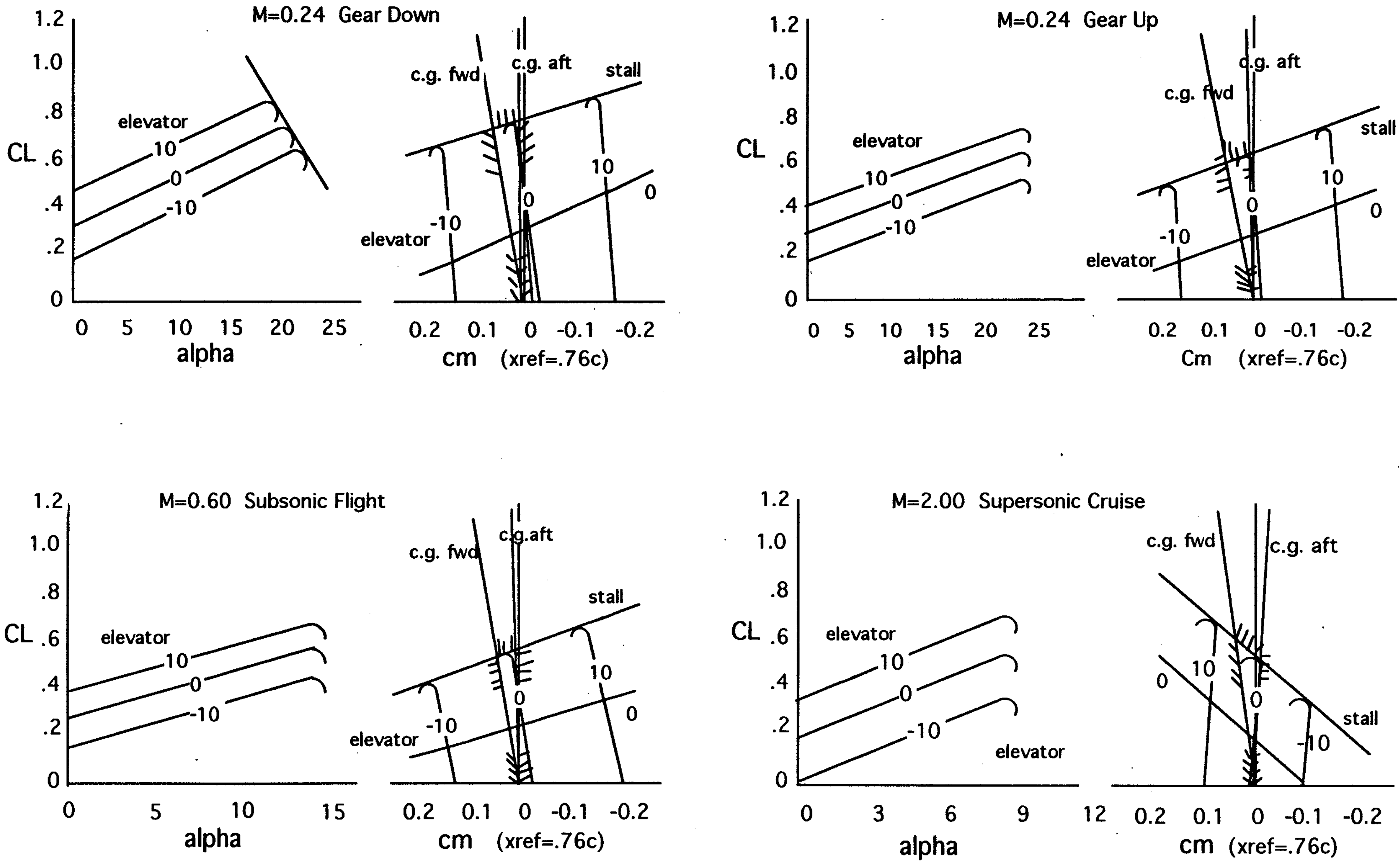


Figure 13.1 Trim Diagrams for Critical Flight Regimes

13.4 HANDLING QUALITIES

Due to inherent instabilities in subsonic flight regimes, stability augmentation is required in pitch and yaw for the Trojan. Control theory has been employed to determine the closed-loop gains required to meet MIL-F-8785C, Level I handling qualities. Military specifications are appropriate in this case because the FAR 25 artificial stability specifications are vague and lacking in definition (Ref. 15). Table 13.3 provides the Level 1 longitudinal and latitudinal flying quality requirements along with the Trojan's flying quality values and necessary feedback gains for the SAS.

C-2

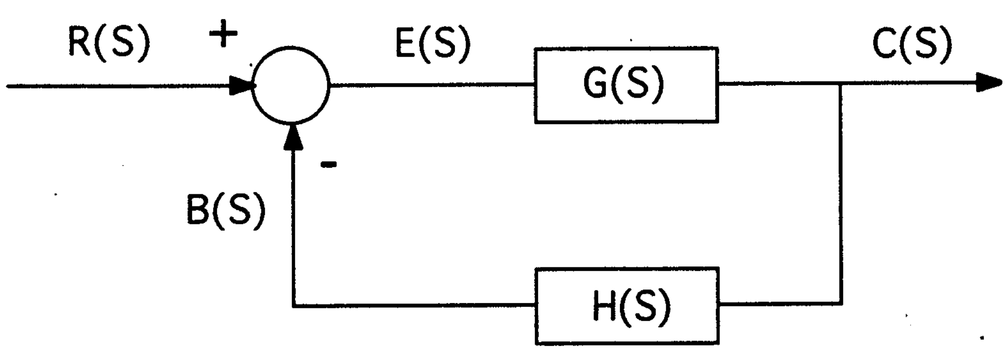
Longitudinal Flying Qualities	Requirement	Flight Condition I		Flight Condition II		Flight Condition III	
Phugoid Frequency (rad/sec)	none	0.17	n/a	0.0738	n/a	0.0237	n/a
Phugoid Damping Ratio	0.04 (min)	0.283	n/a	0.0976	n/a	0.129	n/a
		Augmented	**Gain**	**Augmented**	**Gain**	**Augmented**	**Gain**
Short Period Frequency (rad/sec)	1.5 to 9.0	1.5	23.62	1.5	12.14	1.5	3.24
Short Period Damping Ratio	0.35 to 1.30	0.463		0.821		0.774	
Lateral Flying Qualities							
Dutch Roll Frequency (rad/sec)	1.0 (min)	2.812	-9.73	1.542	-21.59	1.664	-7.09
Dutch Roll Damping Ratio	0.19 (min)	0.283		0.276		0.211	

Table 13.3: Longitudinal and Lateral Flying Qualities

13.5 CONTROL SYSTEM

The Trojan employs a highly reliable control system (Ref. 10). Side stick pilot controls initialize the triple redundant system that uses quick responding fly-by-wire (FBW) controls. FBW replaces mechanical linkages with electrical pulses signalling self contained hydraulic actuators. Three separate main engine generators give the electric power for the FBW system. The auxilliary power unit, the ram air turbine, and the battery system are also available for emergency power.

Figure 13.4 shows the block diagram for the control system employed in the pitch and yaw stability augmentation systems. This block diagram is representative of a common control system (Ref 21).



R(S)	Reference Input	C(S)	Controlled Variable (output)
B(S)	Feedback Signal	G(S)	Forward Transfer Function
E(S)	Actuating Signal	H(S)	Feedback Transfer Function

Figure 13.2: Control System Block Diagram

14.0 SYSTEMS LAYOUT

14.1 FLIGHT CONTROLS SYSTEM

The flight controls utilize a triple redundancy, fly-by-wire system signalling electrohydrostatic actuators. As seen in Figure 14.1, the system originates in the cockpit with pilot input. From there the signals are sent to the flight management computer

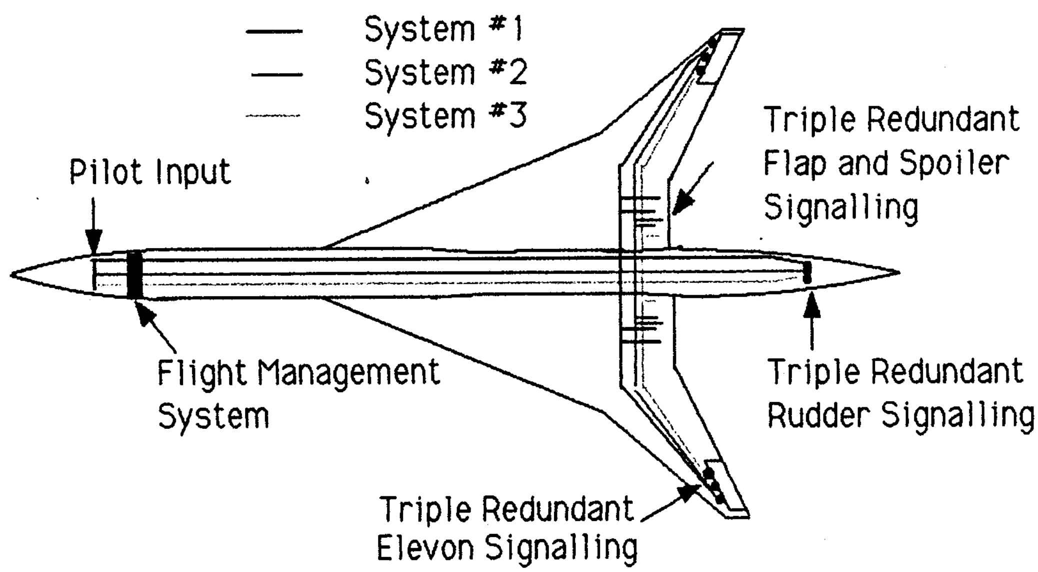


Figure 14.1: Flight Controls System Layout of the Trojan

system located behind and below the cockpit.

The flight management system evaluates the input, and determines which control surface(s) deflection(s) would optimally achieve the desired motion. The signal is then sent to the control surface via three independent circuits. These are located on the left side, right side and along the floor of the fuselage. System separation is also maintained in the wing and tail routing. By separating these systems the chance of a failure in more than one system is minimized. Additionally, for redundancy purposes, each control surface has been divided into three panels, each signalled by a separate circuit and deflected by a separate actuator. Smaller control surfaces also allow for smaller actuators, making for easier installation.

14.2 HYDRAULIC SYSTEM

A layout of the hydraulic system can be found in Figure 14.2. Power to the hydraulic system is supplied by a pump on each inboard engine. The system is also connected to an electric pump, Auxiliary Power Unit, and Ram Air Turbine. This allows for hydraulic power during ground operations when the engines are not running as well as providing the added degree of safety. The system operates at 5,000 psi, a relatively high pressure that offers weight and volume savings. The hydraulic system powers the flaps, landing gear, brakes and steering.

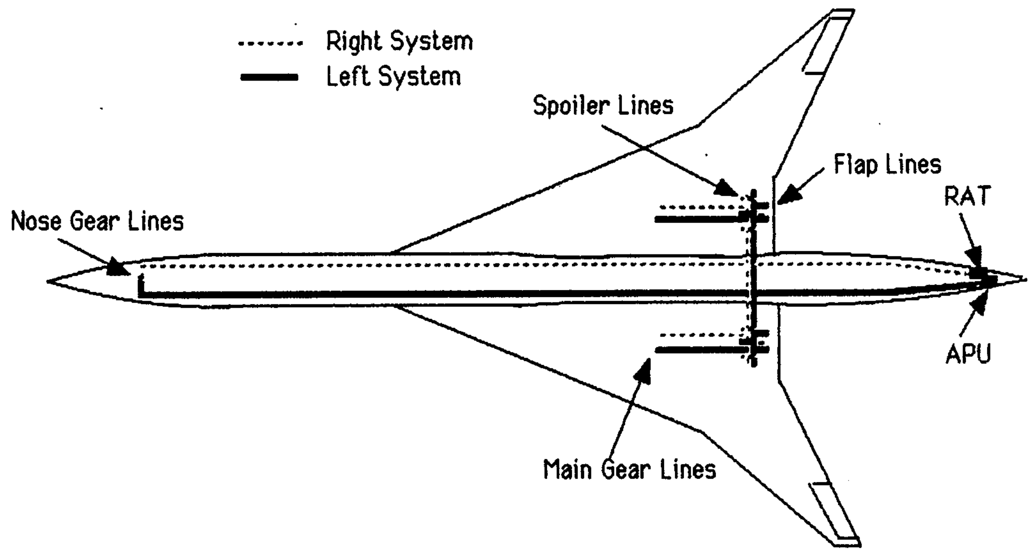


Figure 14.2: Hydraulic System Layout of the Trojan

14.3 ENVIRONMENTAL SYSTEM

The environmental system centers about the mixing and distribution bay located in the center portion of the fuselage as seen in Figure 14.3. Bleed air is drawn from each inboard engine and then mixed and sent to the cabin on the right side. From this major route the fresh air is sent transversely across the ceiling of the cabin where it is released. The air is collected at floor level and sent back to the mixing and distribution bay for filtration, recirculation, and expulsion. Independent systems supply the cockpit, lavatories, instruments, and computer systems as their supply is more critical.

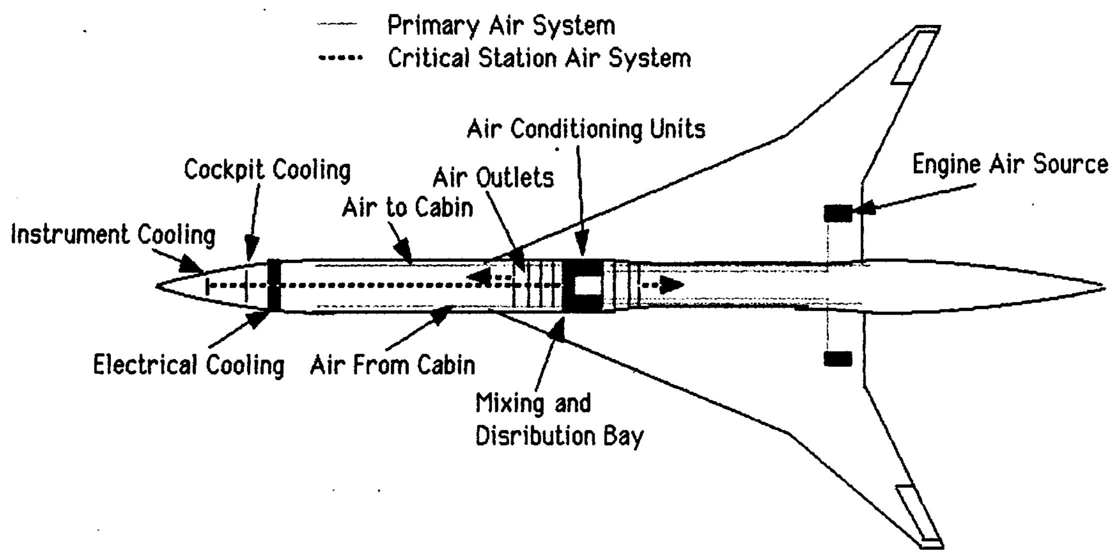


Figure 14.3: Environmental System Layout for the Trojan

14.4 FUEL SYSTEM

The fuel system carries the 6,581 ft^3 of fuel in the inboard portion of the wing's available12,804 ft^3 (see Appendix Part 14). Figure 14.4 diagrams the major components of the fuel system. The fuel system consists of 6 tanks in each wing with the ability to transfer fuel from tank to tank for cruise trim purposes. The tanks located near the fuselage, landing gear and engines are reinforced with stainless steel. Notice also the dry bays in the landing gear and engine areas. Sumps are located at the low point of each wing for release of contaminates. Fueling is done on the left side for compatibility with existing airport facilities. Surge tanks are located in the outermost tanks to gather and condense fuel vapor before venting overboard.

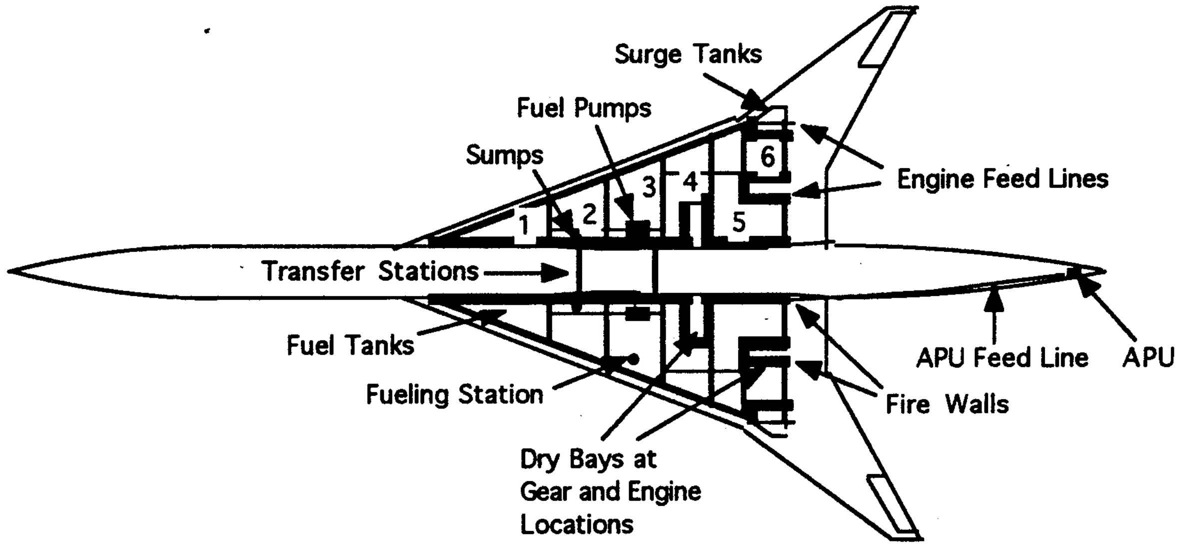


Figure 14.4: Fuel System Layout for the Trojan

14.5 ELECTRICAL SYSTEM

Peak electrical demands of 162 kiloVolt-Amperes were estimated to occur in cruise (Ref. 14). For this reason three engine driven generators delivering 180 kVA were installed. The electrical system, as depicted in Figure 14.5 is powered by the two right engines, and the inboard left engine. The Ram Air Turbine and Auxiliary Power Unit are also connected for emergency and ground operations. The electrical power center and batteries are located aft and below the cockpit. In the case of an emergency, the battery system can supply flight critical systems with power for one hour.

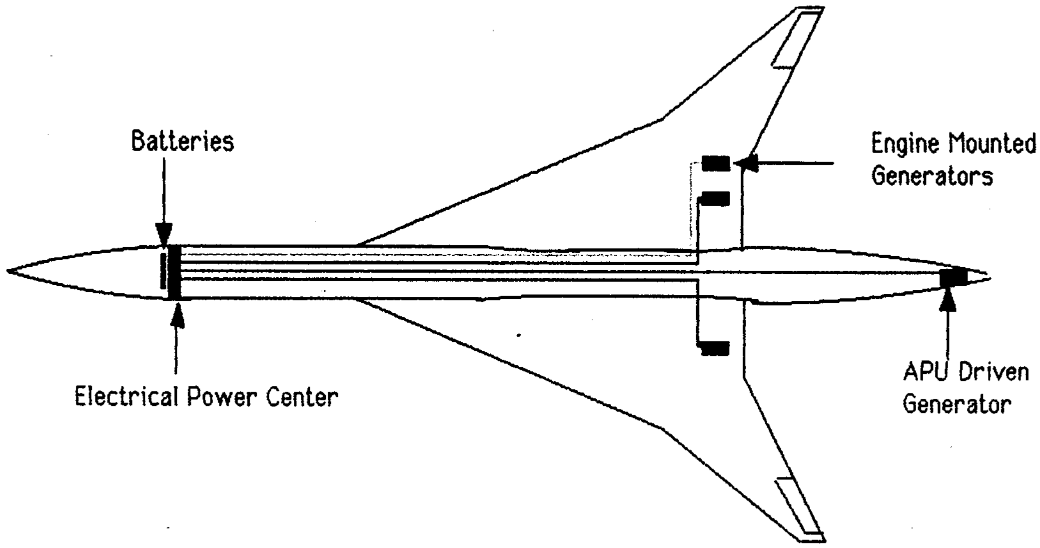


Figure 14.5: Electrical System for the Trojan

15.0 MAINTAINABILITY

15.1 MAINTENANCE REQUIREMENTS

The Trojan was designed to minimize maintenance needs and provide easy access to service key components. Items that require frequent attention, such as avionics equipment and hydraulic actuators are positioned for easy inspection or quick removal.

One such example is the Auxiliary Power Unit (APU). It is located in the aft left-hand side of the plane. Access doors allow the flexibility of either servicing or removing the APU in a minimal amount of time. Inspection doors also aid in diagnosing a possible problem without complete removal of the unit.

Certain concessions, however, needed to be made. There is a tradeoff between the extra weight and easy accessibility of access doors verses the lighter, but harder to get into access panels which require the removal of several screws. Since, weight was such an important factor in the design of the Trojan, access doors are only used in the critical, high maintenance areas of the aircraft. The remaining areas use the weight saving access panels.

15.2 ACCESSIBILITY

The Trojan contains numerous onboard systems that require regular maintenance. For this reason, the various systems are designed to be easily accessible (Fig. 15.2). To simplify access to these components the following features were integrated into the Trojan design.

1. Access panels are located near the hydraulic lines in the wings and fuselage.
2. The fuel pumps can be accessed by doors located right below the pump.
3. The radar and avionics equipment can be removed or inspected by access doors located in the forward portion of the aircraft
4. The right, left and bottom portions of the engine can be exposed by opening access doors.
5. Access doors allow easy access to the APU and RAT.
6. All generators can be reached through access doors.
7. Air conditioning units can be serviced through access panels on the sides of the fuselage.

15.3 ENGINE MAINTENANCE

Engine maintenance covers both the work that is required to maintain the propulsive system in an air worthy condition while installed in an aircraft (on-wing or line maintenance) and the work required to return the engine to air worthy condition when removed from an aircraft (Ref. 22). The Trojan's propulsive system is designed to reduce the time required for both types of maintenance. This is accomplished by three large bay doors that can be opened to access almost the entire engine. If engine removal is required, these doors also aid in the removal of the engine. Internal viewing ports (Fig. 15.1) will also be strategically located to aid in the examination of the compressor and turbine assemblies, nozzle guide vanes, and combustion system.

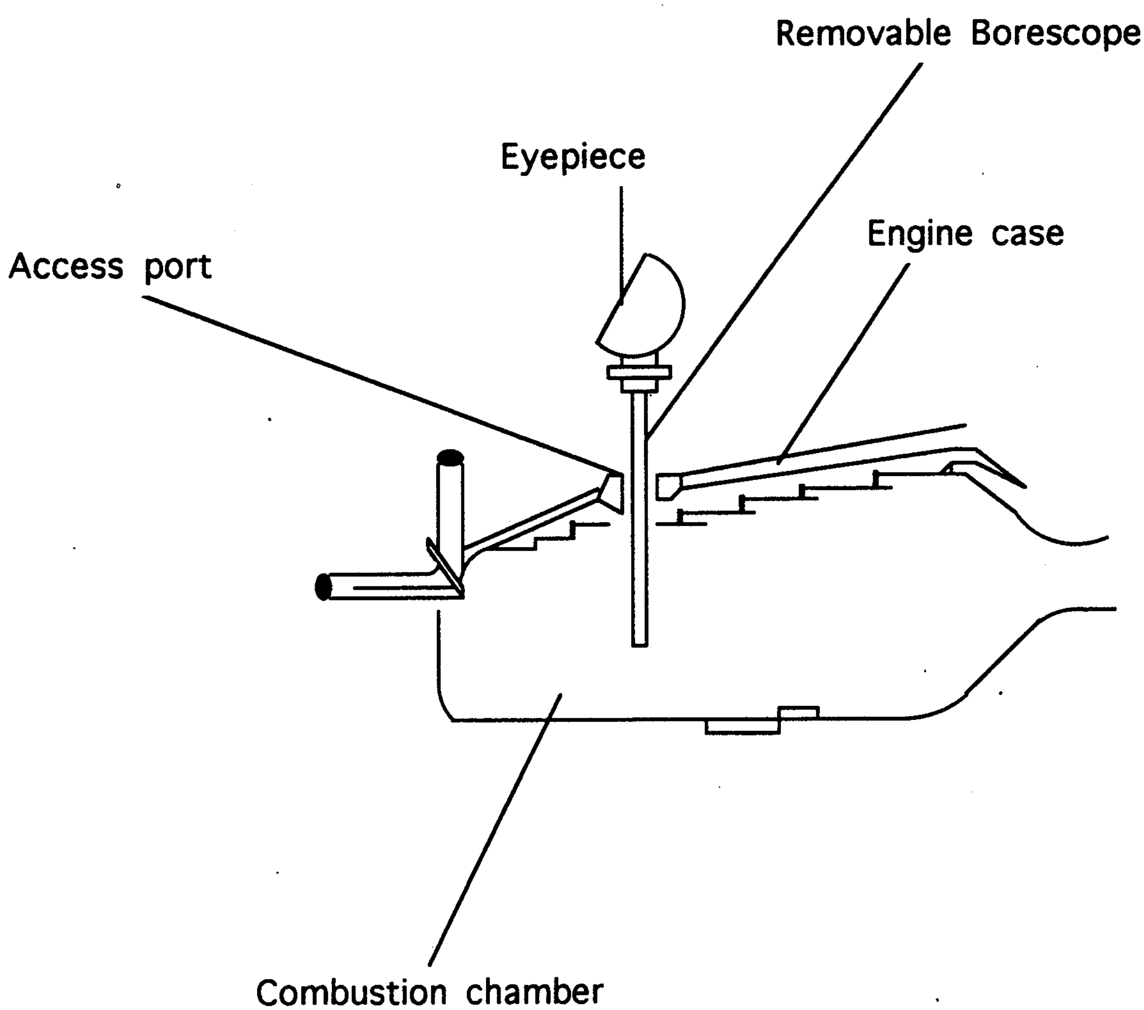


Figure 15.1: Internal Viewing Port

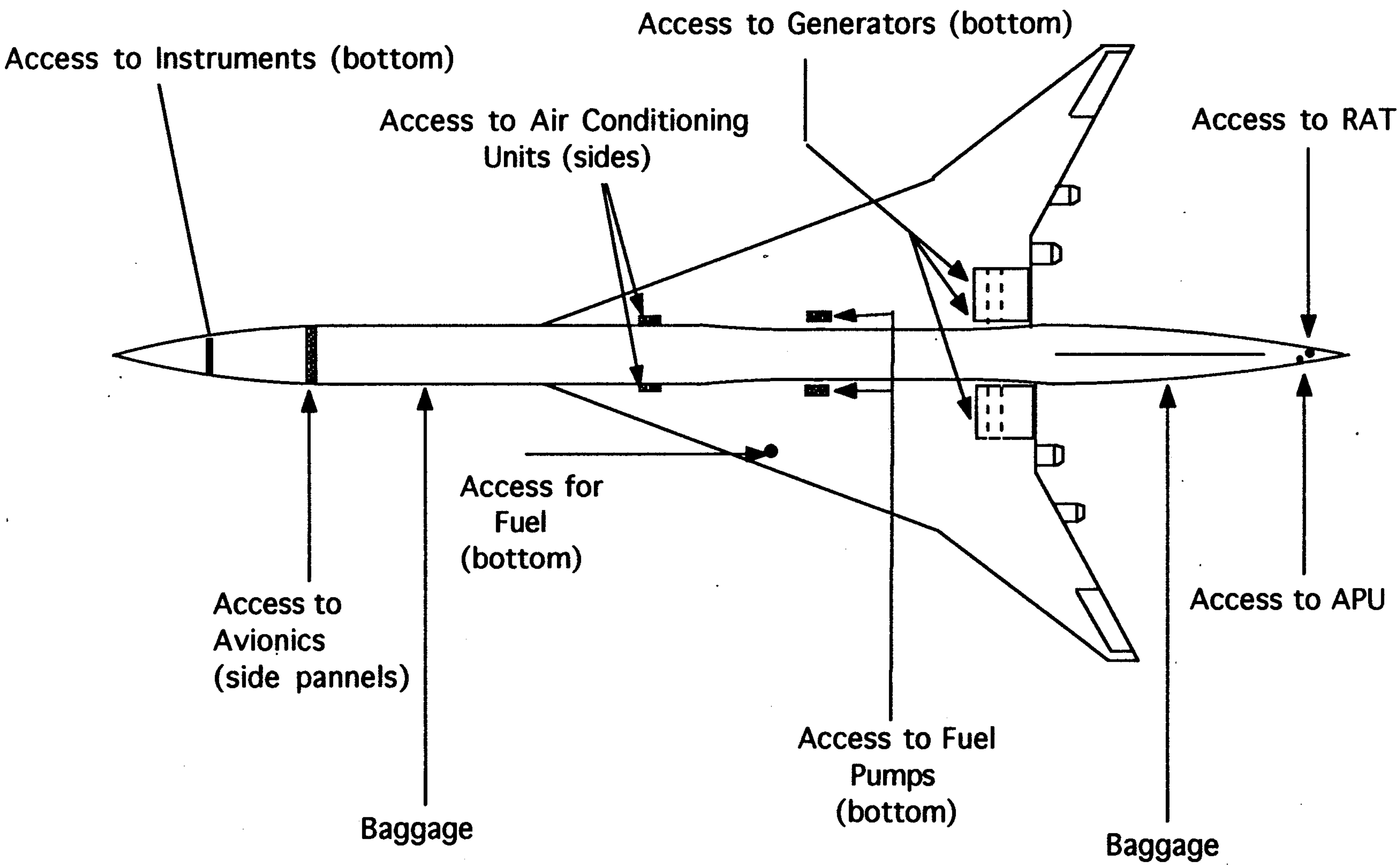


Figure 15.2 Access to Key Components

16.0 MANUFACTURING BREAKDOWN

With the exception of some composites, the Trojan is made of conventional materials. To keep the manufacturing cost down, the Trojan was designed to be assembled in an already existing aircraft manufacturing plant. The construction can be completed without major retooling. Standard assembly techniques can be used for production of the Trojan. Major sub assemblies, such as the vertical stabilizer, could be subcontracted out or produced in a country with much lower labor costs. In order to speed up manufacture, transition from one production activity to the next can overlap. The manufacturing breakdown is shown in Figure 16.1.

Section #	Description	Section #	Description
1.	Fuselag Nose Section	10.	Fuselage-Wing Taper Section
2.	Fwd. Fuselage Section	11.	Wing Center Section
3.	Fuselage Section, Wing Join	12.	Wing Flap Assembly
4.	Fuselage Tail Section	13.	Wing Elevon Assembly
5.	Vertical Tail Leading Edge	14.	Engine Nacelle
6.	Vertical Tail Fwd. Torque Box	15.	TurboFan Engine
7.	Vertical Tail Tip	16.	Main Landing Gear
8.	Vertical Tail Aft Torque Box	17.	Wing
9.	Vertical Tail-Rudder Assembly	18.	Nose Landing Gear

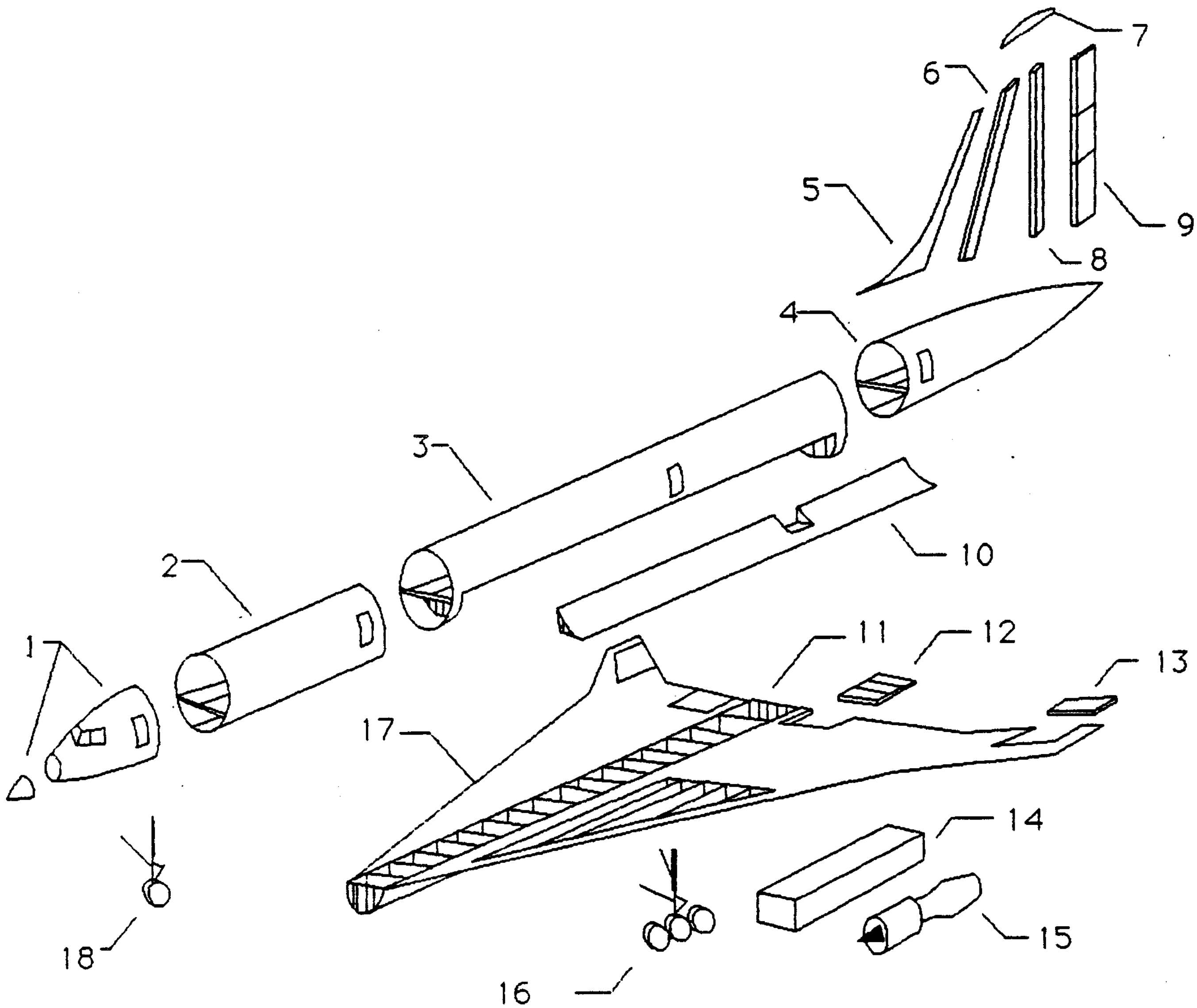


Figure 16.1: Manufacturing Breakdown

17.0 COST ANALYSIS

17.1 COST ANALYSIS METHOD

Since cost is often the bottom line in determining the viability of production, an in depth cost analysis was performed. The economic model used was that laid out in Reference 23. Total life cycle cost is the sum of the Research, Development, Test, and Evaluation (RDTE), Acquisition, and Operating Cost. The economic model allows for flexibility, taking into account variables such as cruise velocity, fleet size, complexity of materials, production date, interest rate, and profit margin. The result of this investigation is a purchase price of $60 billion for a fleet of 300 Trojans, which translates into a price of $200 million per Trojan.

17.2 LIFE CYCLE COST

The life cycle cost breakdown can be seen in Table 17.1 and Figure 17.1. Notice that while the RDTE is a substantial $1.4 billion, it is less than 2% of the life cycle cost. The acquisition of a fleet of 300 Trojans is $4.5 billion, 6% of the life cycle cost. The operating cost of $65 billion is the overwhelming majority of the life cycle cost at 92%. While extensive efforts were made to reduce all costs, since operating cost comprises 92% of the life cycle cost, this is the area in which most energy was directed.

Table 17.1: Life Cycle Costs Breakdown for the Trojan

LIFE CYCLE. COMPONENT	COST (in billions $)
RDTE	1.4
Acquisition	4.5
Operating	65.0

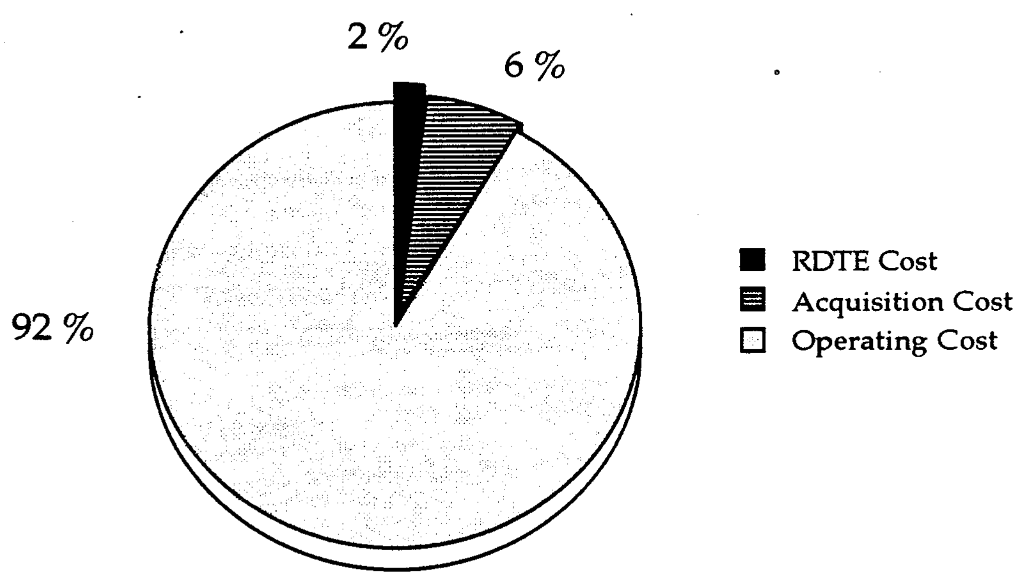


Figure 17.1: Life Cycle Cost for the Trojan

17.3 OPERATING COST

Being that it is such a large portion of the life cycle cost, an in depth study was conducted on the factors influencing operating cost. The operating cost of an aircraft can be broken into direct operating cost (DOC) and indirect operating cost (IOC). DOC's result from expenses such as crew salary, fuel, and maintenance. IOC's are a result of such things as advertising, insurance, and security. The results from the operating cost investigation are depicted in Figure 17.2. It can be seen that IOC's contribute to almost half of the operating cost. Another third of operating cost is attributed to DOC of flight and maintenance. While the expenses of advertising and security are out of the hands of the engineer, the engineer <u>can</u> influence things such as fuel efficiency and maintenance times. For this reason extensive efforts have been made in areas such as propulsive efficiency and ease of maintenance (see section 8 and 15) in order to reduce operating cost.

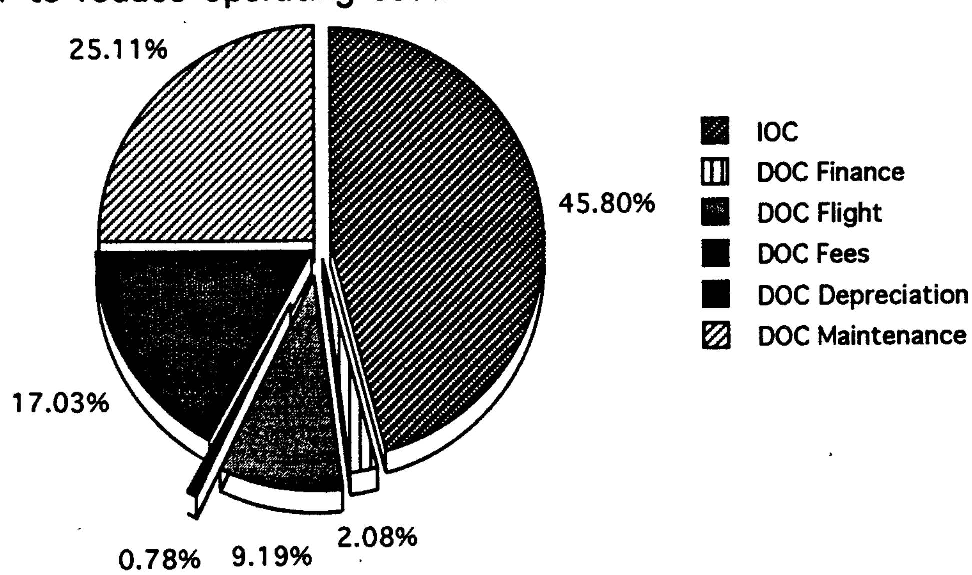


Figure 17.2: Operating Cost for the Trojan

18.0 CONCLUSIONS AND RECOMMENDATIONS

CONCLUSION

The Trojan is a competitive suggestion towards the supersonic transport of the future. This aircraft addresses the issues today's society, primarily those of environmental concern, for instance, reduced emissions and noise abatement. The successful compliance within these parameters only strengthens the Trojan's potential capture of future supersonic air travel.

In addition to societies growing concerns, the Trojan's flight characteristics are favorable. For instance, a Mach cruise number of 2.0 provides for desired times savings without introducing exceptionally high aircraft skin temperatures that require advanced materials development. The 5,200 nautical mile range captures the targeted non-stop Pacific Rim market. Passenger seating capacity of 250 enables efficient and profitable service that encourages the operation of a full aircraft fleet. The airline industry is a highly competitive market, and thus survival is based on profitability of the aircraft they operate. The Trojan introduces profit to a virtually unclaimed regime of flight in the world market.

Overall, the Trojan stands favorably with respect to society and most importantly, the airline industry. Technological advances can only secure the viability and integration of such an advanced aircraft design. Projected trends towards more productive and efficient air travel assures a need for the supersonic transport.

RECOMMENDATIONS

The following aspects of the Trojan merit further preliminary analysis:

Wind tunnel tests should be performed to determine a more accurate lifting curve slope, including stall angles of attack. In addition, stability and control characteristics and derivatives should be verified or corrected from wind tunnel data.

Examination of Table 13.4 shows that a different set of feedback gains for each flight condition are needed. Further development of the Trojan control system will require gain scheduling for variations in Mach number.

The integrated flight-propulsion control concepts for supersonic transports should be further investigated to yield weight savings, reduced specific fuel consumption, and increase overall engine performance.

Aircraft materials will always be an area of research and development in an attempt to provide stronger, more durable and light-weight materials.

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